EFFECTS OF DIFFERENT CLASSROOM NOISES ON SPEECH PERCEPTION

By

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To my family

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Major Department: Architecture

The objective of this study was to find characteristics of classroom noise and noise related factors. Effects of those noise factors on speech perception scores were statistically analyzed. Previous studies have documented the effects of noise level and reverberation in classrooms on speech perception scores. However, the type, spectra, and content of noise found within classrooms and their effects on speech perception were not mentioned. This study showed that noise level decided 70% of the variance in speech perception test scores and other factors explained an additional 20% of variance in speech perception test scores. A noise profiling study was conducted in 41 elementary classrooms in 7 schools in the Alachua County School District in Florida. The effects of classroom noise on speech perception scores of native-English speaking research participants (average 25.5 years old for the first test and 21.4 years old for the second test) were determined. The classroom noise-profiling study showed the dominance of low frequency noise from air-conditioning systems. From statistical analysis, two spectrally different types of noise were found: those with strong low frequency components (SLC) and those with strong high and low frequency components (SHLC). All of the noise levels measured at student-seating areas were higher than the level recommended by ANSI for schools (35 dBA). The effect of noise level on speech perception scores was significant (0.01 significance level) and this study's result was consistent with previous studies. A larger variation in speech perception scores was measured at higher noise levels than at lower noise levels in addition to speech perception test score decrease by increased noise level. Noise spectral effects on speech perception test scores were significant ($p<0.01$) and noise with strong low frequency components (SLC) showed greater reduction in speech perception test scores compared to noise with strong high and low frequency components (SHLC). The specific noise content effect was measured by comparing the difference in speech perception scores between actual noise recorded in classrooms and spectrally adjusted pink noise and its effect was statically significant ($p<0.01$). Annoyance, which has a significant effect ($p<0.01$) on speech perception, was affected by noise level changes. However, spectral characteristics and noise content were not significant for annoyance when 2 spectrally different noises (SLC and SHLC) were applied. The results of this study provide information specifically tied to student performance under actual acoustical conditions in classrooms since real classroom noise sources were used.

CHAPTER 1
INTRODUCTION

Need for Research

In our everyday life, the most commonly used form of communication is vocal. For this reason, a clear transmission of acoustical information is very important. Especially within educational facilities, the importance of clear communication is critical for optimal academic achievement (Crandell and Smaldino 2000). When the subject matter of a class or the language used as a medium is not familiar to students, more stringent acoustic qualities are required to achieve clear communication and better understanding (Nelson and Soli 2000). A more stringent acoustical environment consisting of lower background noise levels and shorter reverberation times is also required when students do not have fully developed communication skills or when they have impaired receptive ability (Elliot et.al. 1979; Heusden et al. 1979; Crandell 1991; Crandell and Smaldino 2000). A classroom's acoustic quality is sometimes measured by speech perception tests. Many factors affect the quality of speech perception. The two most critical factors, reverberation and noise, have been vigorously studied by many researchers. Speech perception is defined as the process of imposing a meaningful perceptual experience on speech input (Massaro 2001). Speech perception can be measured by the percentage of speech units correctly received by a listener. Either word articulation or intelligibility is used. When the units of speech material are meaningless syllables or fragments, word articulation is used. If the units of speech material are complete, meaningful words, sentences, or phrases, word intelligibility is used (Harris 1998).

Speech perception decreases in the presence of noise. Noise masks the source sound. This requires a higher level of source sound to maintain the same level of speech perception. Lochner and Burger (1964) showed the significant link between noise control and speech perception. In their study, a higher articulation score was always measured under quieter noise conditions. Seventy percent articulation was measured at a -10 dB signal-to-noise ratio condition and ninety percent articulation was measured at a -5 dB signal-to-noise ratio. When the signal-to-noise ratio reached +5 dB, nearly 100 percent articulation was measured (Lochner and Burger 1964). Similarly, the deterioration of speech perception caused by a high noise level has been clearly shown by many researchers (French and Steinberg 1947; Licklider and Miller 1960; Nabelek and Pickett 1974 a, 1974 b; Finitzo-Hieber and Tillman 1978; Elliot et al. 1979; Houtgast 1981; Bradley 1985).

The effects of reverberation on speech perception have also been thoroughly studied. Previous studies have concluded that long reverberation times result in decreases in speech perception (Finitzo-Heiber and Tillman 1978; Houtgast 1981; Nabelek and Pickett 1974 b; Locher and Burger 1964). The decrease in speech perception happens because the excessive reverberant sound energy overlaps the direct sound and smears the clear sound spectrum (Nabelek and Nabelek 1994). Unequal sound energy distribution between vowels and consonants can also be a reason for the deterioration of speech perception by extended reverberation. Vowels, which have the most sound energy with less acoustical information, can easily be prolonged by the extended reverberation. These extended vowels cover the consonants which have more acoustic information with less sound energy. Therefore, this results in lower speech perception (Puetz 1971;

Pearsons et al. 1982). The deterioration of speech perception due to reverberation becomes more serious to listeners with sensorineural hearing loss (SNHL) (Finitzo-Hieber, and Tillman, 1978; Crandell, 1991; Bradley, 1985). Details of previous studies on noise and reverberation are addressed in the literature review.

Many researchers have studied the individual and combined effects of noise and reverberation on speech perception. Despite these careful and detailed studies on the effects of noise and reverberation, most research has focused on the effect of the loudness of noise and the length of reverberation on speech perception. However other aspects of noise besides loudness affect speech perception. The following findings support this idea. A noise with the spectral characteristics of speech is considered as the most effective masker (Heusden et al. 1979; Crandell and Smaldino 2000). A low-frequency noise can mask more of the source sound than a high-frequency noise because of the upward spread of masking (Gelfand 1998). A noise with recognizable content can cause conceptual masking, which increases masking effects (Carhart 1969; Elliot et al. 1979). Factors such as temporal characteristics, content of noise, spectral profile, and others should be considered for accurate understanding and prediction of speech perception in addition to loudness.

This study investigated the characteristics of classroom noises and the effect of the level, spectral characteristics, content, and other factors on speech perception. The processes used in this study include a computer simulation study, noise profiling, and human-subject tests. Classroom-noise studies have been performed by many researchers. Although previous noise-profiling studies (Pearsons, Bennett, and Fidell 1977; Houtgast 1981; Markides 1986; Pekkarinen and Viljanen 1991; Hodgson, Rempel, and Kennedy

1999) investigated noises carefully, issues other than loudness were not completely addressed. In the current study both noise level and spectral characteristics of the classroom noises were profiled and statistically analyzed. Based on the statistical analyses, typical spectral characteristics of classroom noises were identified and the effects of the noise spectra on speech perception were studied. Previous speech-perception tests under noise conditions were usually done using either pure tones (Ehmer 1959; Wightman, McGee, and Kramer 1977), filtered random noises (Lochner and Burger 1964; Powers and Wilcox 1977), a multi babble noise source (Finitzo-Hieber and Tillman, 1978; Elliot et al. 1979) or traffic noise that has a similar spectrum to speech (Heusden et al. 1979; Houtgast 1981). In contrast, the current study used the actual noise sources captured in actual classrooms. This will provide information on the actual speech perception that students experience within classrooms. Furthermore, students' responses to different classroom noises, which could not be measured in previous studies can be measured in this study. Therefore, the results of this study will provide information that is specifically tied to the acoustical environment of schools.

Research Objectives

The objectives of the present study were to develop a classroom noise database, focusing on the spectral characteristics and loudness of noise sources and to test the effects of different classroom noises on speech perception to verify previously suggested speech perception related issues under actual classroom noise conditions.

CHAPTER 2

LITERATURE REVIEW AND HYPOTHESIS

Overview

Many studies have been performed to explain speech perception and the changes of perception in different acoustic environments. Those studies made significant contributions to improving our understanding of acoustics and suggested practical improvements that can be made to a room's acoustical environments for better speech perception. Loudness of noise and length of reverberation in the space have been considered as two major factors affecting speech perception.

The current study includes a review of previous studies on various issues that are important in determining speech perception. In addition, the importance of the spectral characteristics of noise is discussed. Based on this view, a relevant hypothesis is drawn that the characteristics of the noise spectrum within a classroom are significant in determining speech perception.

Sound Sources

With the exception of very large lecture rooms or special classes for hearing-impaired students, most classes are conducted using natural acoustic speech projected by the teacher. In this case, the sound source is a crucial factor for clear communication.

Pearsons and colleagues' (1977) study characterized teachers' voices used in classrooms. Loudness of voices for a range of raised or loud vocal effort were measured between 67 dB and 78 dB at 1 meter distance in L_{eq}. It is difficult to maintain a high-level vocal effort throughout a class period because of the limitations of vocal efforts. In consideration of this fact, Bradley examined low expected vocal levels during classes (55-63 dB, female at 1 meter distance) (Bradley 1985). The background-noise level of occupied classrooms, with no talking during a test was 45 dB (L_{eq}). A study on background noise and teacher's voice level showed an interesting relationship between them. When background noise was increased, teachers' vocal efforts increased at the rate of 1 dB for each increase of 1 dB in background noise from 45 to 55 dB (Pearsons et al. 1977).

The teacher's vocal level heard by students is strongly affected by the distance between a teacher and a student. In outdoor conditions with minimal reflections from other objects and where the sound source is located above ground (similar to an anechoic chamber condition) the sound level decreases as the square of the distance from the source; a 6 dB sound-level decrease for every doubling of the distance between the source and receiver (Knudsen 1932). However, sound within a confined space, such as a classroom, does not follow this "inverse square law." The sound-attenuation rate will be less than 6 dB per doubled distances. The sound reduction will be decided by the characteristics of a room (such as size and sound absorption). With more sound absorption, sound will decay at a faster rate. In an odd shaped room, sound will not decay uniformly or acoustical defects (such as an echo or flutter echo) can occur due to a large gap between the outstanding reflection and the direct sound (Knudsen 1978).

Spectral and Loudness Characteristics of Voice at Different Vocal Efforts

Some loudness differences were found between male and female voices. These loudness differences also vary with vocal effort. Pearsons and colleagues' study (1977) measured only small differences (2-3 dB) between males and females at low vocal efforts (Figure 2-1). However, the differences increased (5-7 dB) at elevated vocal efforts.

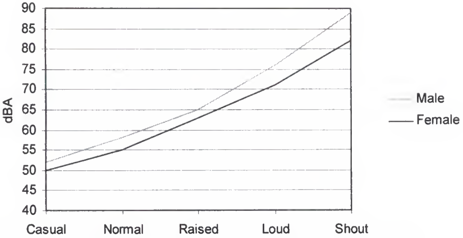

Figure 2-1. Male and female voice level under different vocal efforts

The spectral characteristics of males and females are similar during normal vocal effort conditions. Byrne et al. (1994) performed extensive research on longer-term average speech spectra using 12 different languages. According to their study, males and females showed similar speech spectra and speech levels. The average value of male voices was 71.8 dB, while that for females was 71.5 dB. Measurements were taken at a distance of 20 cm from the talker's mouth. Almost identical speech spectra were found over the frequency range from 250 to 5000 Hz. However, for frequencies of 160 Hz and below, male levels exceeded female levels because of the difference in the fundamental frequency ranges. A similarity between the general speech spectra of male and female voices was also found in Pearsons and colleague's (1977) study: as vocal effort increased, speech spectra showed a trend toward greater high-frequency content.

Temporal Characteristics of Speech

Figure 2-2 shows sound-level variations, which were measured during lectures in different classrooms by different researchers. Variations were found in the measurement results because of differences among speakers and acoustic environments. The average sound level of the speakers varied from 60 to 70 dB. Minimum and maximum sound-level variations ranged from 10 to 30 dB. According to Dunn and White (1940), the dynamic range of speech levels was about 36 dB. Beranek (1947) showed a reduced value of 30 dB in measurements without pauses.

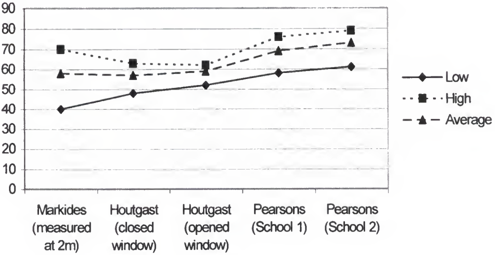

Figure 2-2. Variations in speech levels found in previous studies

Because of the lack of detailed information on measurement methods, it is difficult to conclude which crucial factors caused this variation. However, one of the main reasons for the speech-level fluctuations is the temporal characteristics of the human voice. Houtgast's (1981) study showed continuous loudness fluctuations. These fluctuations came from the sound-energy difference in phonemes. Sound-level fluctuation during speech is fairly common. This could happen even when prepared text materials are recited.

This fluctuation was found in Byrne and colleagues' (1994) different language comparison study. This study was made on the basis of records of reasonably fluent readings in 13 different languages (without pause) for at least 64 seconds. Various measurements were taken with 13 different languages and those results were compared to a normalized L_{eq} . From this comparison, low level of L_{99} (more than -20 dB), high peak level (about 20 dB), and high level of L $_1$ (about 5 dB) were commonly measured. These data verify the loudness fluctuations for the 13 tested languages (Byrne et at. 1994).

When there is fluctuation in speech and intense competing noise, part of the speech with low energy can be easily masked by noise resulting missing acoustic information. This can cause a problem for listeners who do not have enough information to fill in the missed information (semantic closure) or who do not have fully developed language abilities (Elliot et al. 1979).

Noise

Noise can be defined as any disagreeable or undesired auditory stimuli or unwanted sound. Using an electric wave analogy, this can be extended to include any unwanted disturbance within a useful frequency band (Harris 1998). In classrooms, noise interferes with what students want (or need) to hear and understand (Crandell et al. 1995).

Various noises can be found within a classroom. Markides (1986) categorized classroom noises into 3 different types (Table 2-1): short-duration noise (foot steps, banging of doors….); nonstationary long-duration noise (competing speech by students, and speech-like noise); and quasi-stationary noise (cars, airplanes, trains, and heating and ventilation noise: hard to control, mostly from outside).

Table 2-1. Markides noise classification

Noise types	Sources
Short-duration noise	Footsteps, banging of doors and desk lids, opening and closing of drawers, opening and closing books
Non-stationary long duration noise	Chattering (competing student speech and speech-like noises)
Quasi-stationary noise	Machinery noise, traffic noises, HVAC noise

Noises can also be classified into two groups depending on their temporal characteristics: continuous and transient (Steele 1971). Transient noises (such as intruding noise from outside and noise from students' activities during class) have large sound-level fluctuations during short time durations. Continuous noise has small sound-level fluctuations. Possible constant-noise sources are poorly designed HVAC systems and audio-visual equipment with loud cooling fans. Noise from HVAC systems is considered as the primary noise in classrooms (Siebein et al. 2000^2).

Various single-number descriptors are currently being used in noise-level measurements. The most frequently used single-number descriptors are spectrum-shaping networks (dBA, dBC, or dBB), noise criteria (NC), and room criteria (RC). Due to the complexities in the human hearing mechanism, sound-level-meter measurements could not reflect the ear balanced loudness level. Therefore, spectrum-shaping networks were designed to meet the sound level meter measurements with approximate perceived loudness level (American tentative standard 1936). Different types of spectrum-shaping networks were designed to approximate the loudness level sensitivity of human hearing to low-, medium-, or high-level pure tones. The A network gives response characteristics that are approximately the inverse of the 40-phon equal-loudness contours for pure tones. The B and C network are the inverse of the 70- and 100-phon equal-loudness contours. The A network was recommended when the sound meter reading was between 24 to 55 dB, the B network for readings between 55 to 85 dB, and C network for readings above 85 dB. (American Standard Z24-3 1944; Beranek 1954). The most commonly used spectrum-shaping network is A-weighted sound levels (dBA). This method is the best single-number rating for assessments of hearing or health damage, work tasks interference, speech communication interference, privacy affection, sleep interference, and noise induced annoyance (Beranek 1971). C-weighting is used to prevent an

---

excessive response of the sound meter to signals outside the audible frequency range by limiting the low and high frequencies. B-weighting is rarely used (Bruce 1971). However this method cannot properly reflect the spectral characteristics of noise. The same noise level can be measured from a number of spectrally different noise sources using this method (Crandell 2000). Noise criteria (NC) is widely used in evaluating noise in buildings. The NC rating is determined by measuring the sound pressure level of noise over each octave band and comparing the spectrum with established NC curves. The NC rating will be decided by the lowest NC curve not exceeding the measured noise spectrum (Beranek 1957). However, when the noise spectrum is similar to the NC curve, the sound can be "hissy" or "rumbly" (Beranek 1971). In addition to that, the NC rating using the tangent-contour method (NC curve tangent to the noise spectrum) cannot give useful information about the noise spectral characteristics that might have adverse effects on hearing. Sometimes the same NC rating can give different subjective feelings such as hissing and rumbling (Blazier 1991). The RC method is recommended as a preferred alternative to either the NC method or the A-weighed sound level to specify the maximum level in a room supplied by an HVAC system. The RC method takes into account the influence of both spectrum shape and level on the subjective assessment process. Especially by adding two special regions at high levels (from 65 to 75 dB and from 75 to 85 dB) of low frequency sound energy (16 and 31Hz), vibration problems in lightweight building construction can be considered (Blazier 1991). The NCB method (Balanced Noise Criteria Method) is designed to measure both room noise and noise from occupant activities. This method uses a series of NCB criteria curves which are designed to replace the NC curves and include two low frequency octave bands (16 and 31 Hz).

Permissible sound levels in the high frequency octave bands (4000 and 8000 Hz) by the NCB method is around 5 dB lower than that of NC (Beranek 1989; ASHRAE Application Handbook 1999). The RC Mark II method is a revised version of the RC method. Like the RC method, the RC Mark II method is designed to rate the sound performance of an HVAC system as a whole. Thee RC Mark II method includes quality assessment procedures, which use three separate bands (low: 16, 31.5, and 63 Hz; mid: 125, 250, and 500 Hz; high: 1000, 2000, and 4000 Hz) and equations, these procedures make this method is more complicated than the RC method. However due to its complexity, the RC Mark II method can measure noise spectral balance (Blazier 1981; ASHRAE Application Handbook 1999).

Table 2-2. Comparison of sound-rating method

Method	Noise Interfering Effects on Speech Intelligibility	Sound Quality
Noise Criteria (NC)	Considered	Not evaluated
Room Criteria (RC)	Considered	Evaluated
Spectrum-shaping networks (dBA, dBC)	Considered	Not evaluated
Balanced Noise Criteria (NCB)	Considered	Evaluated
Room Criteria (RC Mark II)	Considered	Evaluated

Table 2-2 shows the ASHRAE's (1999) comparisons among different sound rating methods. All ratings in the table consider interfering effects of noise on the intelligibility of speech (ASHRAE 1999). The noise level from air-conditioning units varies depending on the types of systems and the system design. Siebein and colleagues (2000) took classroom noise measurements in rooms with different air-conditioning systems. Their study included several common air-conditioning unit types: self-contained wall mounted units; decentralized fan coil units; heat pumps with short duct runs; central rooftop units serving multiple rooms; and central systems with variable air volume controls. According to their study, noise levels as high as NC55 (61 dBA) were measured from the wall-mounted units and decentralized heat pumps with short duct runs. Central systems with sufficient duct lengths to attenuate sound showed the lowest average NC levels of 35 (43 dBA).

Table 2-3. Frequency ranges of noise sources and related sound quality

Noise source	Frequency range (Hz)	Quality
Fan instability, Air turbulence, and Structure-born vibration	16–63	Throb or Rumble
Fan, Pump	63-500	Rumble, Roar
VAV Unit Noise	125-2000	Roar, Whistle and Whirr
Reciprocating and centrifugal chiller	250-1000	Roar, Whistle and Whirr
Diffuser	500-4000	Whistle and whirr, Hiss

Noise from HVAC can be characterized according to the noise problem sources and different noise sources show different noise spectra. Table 2-3 shows those relationships. Fan noise and air turbulence contribute to low frequency (16, 31.5, and 63Hz) sound levels, VAV(Variable Air Volume) units contribute sound levels in the range of 125Hz to 2000Hz, and noise from air distribution systems contributes to high frequencies (from 1000 to 4000Hz) (ASHRAE Hand Book 1999).

Noise Measurements

Markides (1986) measured speech and background noise levels in 12 school classrooms during classes. The levels of background noise varied from 45 dBA (the average level of the ventilation system and general hustle and bustle of the school) to 77 dBA (the average level of short duration noise such as banging doors, desk lids opening, and closing drawers). From Houtgast's (1981) study, a mean value of 57 dBA was measured as the teacher's speech level in the classroom. Lower sound levels than that of the teachers' voice, ranging from 45 to 55 dBA, were measured as background noise levels. From a study of 31 school classrooms, both occupied and unoccupied, Pekkarinen and Viljanen (1991) reported 40–58 dBA student-activity related noise and 23-49 dBA ventilation noise levels. From a study of average speech levels against different background noise levels, Pearsons and colleagues (1977) measured 48 to 51 dBA classroom background noise. Furthermore they also claimed that vocal effort increases 1 dB for every 1 dB increase in background noise when the range of noise is between 45 to 55 dBA. Hodgson, Rempel, and Kennedy (1999) took measurements during 18 university lectures in 11 classrooms. From this study, they found three typical background and noise levels: ventilation noise of 40.9 dBA; student-activities noise of 41.9 dBA; total background noise of 44.4 dBA; and a speech-signal of 50.8. Table 2-4 shows a summary of previous studies.

There are various noise sources within classrooms. Different noise sources have different spectral characteristics as well as different noise levels. However, most of the previous studies did not mention the spectral composition of the wide variety of background noises and sources. Noise sources with equal overall sound levels are expected to be equally loud. However, the spectral characteristics of sound sources with the same overall sound level can cause different hearing perceptions. That means that the spectral characteristics of noises have different effects on listeners. In a critical noise level study which measured a teacher's bother-threshold, Houtgast (1981) suggested when there is a -15 dB signal-to-noise ratio the noise will interfere with source sound. He also mentioned the possibility of a 5 dB variation in noise level by oversimplification of noise by not considering a variety of spectral and temporal characteristics of noises.

In order to understand the actual effects of noise on hearing, the spectral characteristics of sound should be considered as well as the sound level. The current study was designed to find the spectral characteristics and the levels of noise within classrooms. The study was limited to regular educational spaces. Special-purpose classrooms, teleconferencing rooms, special education rooms (those for severely acoustically-challenged students or other spaces), and large auditoria were excluded from this study.

Table 2-4. Typical speech and noise levels in classrooms from previous studies

	Speech (dBA)	Noise level (dBA)		
Markides	Range: 40-70 Avg.: 57.5 Std.: 8.4	Range: 50-65 Avg.: 59.8 Student activities	Range:60-92 Avg. 76 Short duration noise	Range: 40-50 Avg.: 44.6 Ventilation
	At 2m distance	At center of the room		
Houtgast	Range: 48-63 Avg.: 57 Std.: 5	Range: 45-55 Avg.: 47.4 Std.: 3.1 Road traffic noise, w/ window close		
	At 1m distance	Some distance away from teacher, wall, and window		
Pekkarinen and Viljanen	Range: 58-79 Avg.: 67 Std.: 5	Range: 40-58 Avg.: 49 Std.: 6 Students activity	Range: 23-49 Avg.: 33 Std.: 5 Ventilation	
Pearsons, Bennett, and Fidell	Range: 67-78	Range: 48-51		
	At 1m distance	Average of front and back seating		
Hodgson, Rempel, and Kennedy	Range: 43-59 Avg.: 50.8 Std.: 3.9	Range: 30-50 Avg.: 41.9 Std.: 4 Student activity	Range: 32.6-47 Avg.: 40.9 Std.: 3.9 ventilation	Range: 35-51 Avg.: 44.4 Std.: 3.5 Total
		Three or four positions in 11 classrooms		

Reverberation Time

With the exception of outdoors or anechoic chamber conditions, every sound is composed of 2 parts: direct sound and reflected sound. The direct sound is closely related to the characteristics of the source and its variation by room conditions is very limited. Meanwhile, reflected sound (early reflected sound, late reflected sound, and reverberant sound) is influenced by the shape, the size, and the reflective and absorptive properties of a room (Knudsen 1978).

Sound reflections within a very short time after the direct sound combine with the direct sound to increase the loudness (Thiele 1953; Lochner & Burger 1964; Bradley 1986) and this sound energy addition improves speech perception (Nabelek 1994; Siebein et al. 1997). Hass (1972) indicated that sound loudness and liveness could be enhanced by early-reflected sound which arrives within a 30ms time delay of the first arriving sound. However, excessive reverberation can cause excessive loudness and deteriorate speech perception (Siebein, Crandell, and Gold 1997).

The sound environment can range from the near field to the diffuse (reverberant) field. Distance from the sound source mainly decides the characteristic of the sound field of a typical noise source. Particle velocity is not necessarily in the direction of the propagation of the sound wave in the near field and an appreciable tangential velocity component may exist at any point. In this field, a significant amount of sound variation exists as a function of the distance from the source. Therefore, measurements in the near field can give data with large variations (Wiener 1960). The distance from the source to which the near field extends depends on frequency, source characteristic dimensions, and phases of the radiating parts of the surface of the source. Establishing the accurate limits of the near field for an arbitrary source is difficult (Beranek 1971). The remaining region beyond the near field is called the far field. In the far field with no reverberation (anechoic chamber condition) the inverse square law, a 6 dB decrease in sound pressure level with every doubling of distance from the sound source, can be applied (Knudsen 1950). In this field the direction of particle velocity is the same as the sound wave propagation direction (Beranek 1971). Sound is reflected from all possible directions and the sound energy density is nearly uniform in the diffuse field, also called the reverberant field (Beranek 1971). The diffuse field is a basic assumption, which is used in the analytical RT measurement method, for Sabine and Eyring reverberation time measurement methods. In a diffuse field, reverberant sound energy comes from all directions with equal intensity and measured RTs are the same at any position (Hodgson 1996). In theory, RT is defined as the time, in seconds, which a sound level in a reverberant sound field takes to decay 60 dB after the sound has stopped. The ISO standard measures reverberation time by the sound decay rate measured from the decay curve from a level 5 dB below the initial level to 35 dB below (ISO 1997). Sound decay can also be measured by Early Decay Time (EDT). EDT is measured from the first 10 dB sound decay then decay time is multiplied by a factor of 6 (Jordan 1970).

Reverberation Time measurement Methods and Factors

Analytical Methods

The Erying and Sabine methods are commonly used to estimate reverberation time. Both methods assume complete sound diffusion. In a diffuse sound field, the reverberant sound waves are incident from all directions. This is the same at every position in the room (Hodgson 1996). In a real situation, due to the lack of complete diffusion, analytical RT measurement methods tend to underestimate the RT (Bistafa and Bradley

2000). The Sabine formula is commonly used to predict reverberation time and is given in Equation 2-1 (Sabine 1922).

$$T = \frac{KV}{\alpha} \tag{2-1}$$

T=duration of residual sound
V=volume of any room [cubic meter]
K= ratio of the parameter to the volume, [0.164]
α=absorption power of the room

When this formula 2-1 is converted into English units

$$T = 0.05\frac{V}{\sum S\alpha} \tag{2-1a}$$

V=volume [cubic feet]
S=surface areas of the various materials in the room [square feet]
α=absorption coefficient of each material

Table 2-5. Sabine and Erying RT ratio under different absorption condition

Room Absorption (â)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Sabine RT/ Erying RT	1.1	1.1	1.2	1.3	1.4	1.5	1.7	2.0	2.6	36.7

Table 2-5 shows that the RT from the Sabine formula is longer than that of the Eyring formula under a high room absorption condition. However, this difference decreases as the total amount of sound absorption in the room decreases (Bistafa and Bradley 2000). Sabine's prediction model is accurate for low average surface absorption coefficients (Hodgson 1996).

$$T = -0.05\frac{V}{S\log_e(1-\alpha_a)} \tag{2-2}$$

V=volume [cubic feet]
S=total surface area of the room [square feet]
α_a=average coefficient of absorption

Eyring's RT formula is shown in Equation 2-2 (Eyring 1930). In spite of its convenience and accuracy under low absorption conditions, Sabine's RT measurement

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method cannot be an accurate RT measurement for high absorption conditions. Under ideally complete absorption condition (â =1), reverberation time should be zero. However, the Sabine formula does not give zero reverberation time when â is 1. Eyring's formula was developed to improve the deficiency of the Sabine method under high absorption conditions. For any average surface absorption coefficient, the Eyring formula is accurate (Hodgson 1996). 'Engineering accuracy' defined roughly as accuracy of ±10% in reverberation time was used in Hodgson's study. The accuracy of both the Eyring and Sabine formulae may decrease in certain rooms with non-uniform surface absorption, commonly found in many classrooms where only the ceilings have sound absorbing material.

Bistafa and Bradley (2000) varied the sound-absorption treatments in a simulated classroom, and their experimental results were compared with many different analytical reverberation time prediction models: Sabine; Eyring; Milington; Cremer; Kuttruff; Fizory; and Arau-Puchades methods . They found that none of methods was within the required 10% accuracy and none could be singled out as more accurate than the others. The range of overall average relative errors was between 17.4% and 65.7%. They concluded that since the simplicity and average accuracy was comparable to the best prediction, the Sabine and Eyring formulae are reasonable choices for RT estimates.

Field Measurements

During field measurements, T30 is most commonly used in reverberation time measurements. RT is measured from a 30 dB sound decay. RT is obtained by doubling the time measured for a 30 dB decay (T30) (ISO 1997). T30 can be measured by either the interrupted noise method or the integrated impulse response method. The interrupted noise method, which is similar to Sabine's method (1922), measures T30 from the decay of omni-directional pseudo-random broadband or band limited electrical noise source after stopping the noise source in a room. Due to the randomness inherent in the source signal, averaging over a number of measurements (minimum 3) at each position is required. The integrated impulse response method which was first proposed by Schroeder (1965), measures the decay curve by reverse-time integration of the squared impulse response. This method removes the effects of the fluctuation in the decay curve without averaging of multiple measurements and easily detects the existence of multiple decay rates (Schroeder 1965). A burst noise with sufficiently flat spectra and sufficient power for the required signal-to-noise ratio or a pseudorandom noise based on "maximum-length" sequences are used as noise sources for the measurement. Using a pseudorandom noise improves the signal-to-noise ratio. The dynamic requirements on the noise source can be considerably lower than the interrupted noise method (ISO 1997). Early decay time (EDT) is a modified measure of reverberation time. It measures the time required for the first 10 dB of decay, multiplied by 6 to extrapolate the result to a 60 dB decay (Jordan 1970). Substantial variation of room shape cannot be represented by the overall reverberation time. The overall sound decay is decided from numerous reflections which are arriving with different delays and strengths from sound reflecting surfaces. Unlike the overall reverberation time, EDT is determined by only a few strong and isolated reflections. Therefore, EDT is sensitive to measurement location and details of room geometry (Kuttruff 1991).

Differences between predicted and measured RTs often exist because many room spaces are not able to satisfy the basic assumption of the complete diffusion condition required in the analytical RT measurement method. Bistafa and Bradley [2] (2000) used a

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simulated classroom with different sound-absorption treatments (i.e., 10 different sound-absorbing configurations) to compare the difference between experimental and predicted reverberation times. According to their results, the errors from the predicted and experimental reverberation times changed with different absorption configurations. Predicted reverberation time was accurate in one situation and over some frequency bands but failed in another. They summarized the results from 10 different configurations and compared them to get overall average relative errors of the analytical predictions of reverberation time. Three different groups were used in their comparison: 1k Hz; mid-frequencies (500 Hz, 1k Hz, and 2k Hz); and six octave bands from 125 Hz to 4k Hz. The study results showed that the relative error of the Sabine method in the 1 kHz band was larger (38.8%) than the relative error at the mid-frequencies (31.6%), which was larger than the relative error across the six octave bands from 125 Hz to 4k Hz (21.5%). The Eyring method also showed similar results: 1k Hz (42.6%); mid-frequencies (35.7%); 125 Hz-4k Hz (24.7%). As shown in Bistafa and Bradley's results, the relative errors between predicted reverberation times using analytical methods and measured reverberation times reduced as more frequency bands were included in the averages.

Even though the ANSI S12 standard uses averaging of three different octave band frequencies (i.e.: 500, 1k, and 2 kHz) and ISO 3382 (1997) also allow averaging of reverberation times in the 500 Hz and 1000 Hz octave bands for a single reverberation time figure, an averaging process may cause loss of detailed information in each frequency, which is important in acoustical analysis. Errors found in their study were huge, more than 10% of an 'engineering accuracy' (Hodgson 1996), in both individual and averaged cases.

Factors Affecting Reverberation-Time Measurement

Sound Scattering (Surface Scattering and Volume Scattering)

Sound can be scattered by two different scattering mechanisms; surface scattering and volume scattering. Surface scattering is the ratio of non-specularly reflected sound energy to totally reflected energy. It is measured by the scattering coefficient δ. Volume scattering, obtained by multiplying the density of scatters by the average scattering cross section, is measured by the scattering frequency $v[m^{-1}]$. Furniture inside of a room can provide volume scattering (Bistafa and Bradley[2] 2000). As sound scatters by surface scattering or volume scattering, room surfaces can be hit by sound in a more uniform manner and absorbing surfaces can be better utilized. This becomes more important when sound-absorbing material is not evenly distributed inside a room. Details on the effects of absorbent material distribution on reverberation time will be discussed. According to Hodgson's (1996) study, Eyring prediction is accurate only under the existence of an optimum value of the volume scattering density. The optimum value depends on the room shape and surface-absorption distribution. In general, the value is low in regularly-shaped rooms with uniformly distributed absorption. The optimum value increases with room aspect ratio and non-uniformity of absorption. In Hodgson's (1994) study, which used a test room with dimensions of 30m x 15m x 5m; the absorption coefficient of all surfaces was 0.1, and it showed optimum volume scattering density of 0.05 for the sound decay to agree with that predicted by the Eyring formula. However, when the volume scatter density is different from the optimum value, measured sound decay was longer than predicted by the Eyring's formula. For example, when the times for 30 dB decay were measured, 2.5 , 1.5, and 1.3 sec were measured for 0, 0.01, and 0.05 volume scatter density respectively.

Surface Absorption Material Spatial Distribution

The amount of sound absorbent material and its spatial distribution affect the RT results. When a room has a predominant absorption surface, sound decay curves will be double-sloped or non-linear. This non-linearity or double slope results from sound traveling in some directions being quickly absorbed, resulting in a fast initial decay, while sound in other directions lingers due to low absorption and yields a slower late decay (Dalenback 2002). Bistafa and Bradley[2] (2000) also tested the effect of surface absorption material configurations on reverberation time. According to their study, a concentration of sound absorbent material on some room surfaces tended to produce reverberation times longer than the same amount of absorption material more uniformly distributed on room surfaces because of lasting sound reflections by hard surfaces with less attenuation. According to their study, when same the absorption treatment was used on the same total area (equal to 52.4% of the ceiling area), different configurations showed different reverberation times. When only the end wall and part of the ceiling was treated with absorptive material the measured RT was 1.6 sec while 1.1 sec were measured when the upper part of the walls or ring of the ceiling were evenly treated. From their study maximum 0.5 sec reverberation time differences were measured from absorption material spatial distribution differences.

Room Shape

Analytical RT measurement methods, especially the Erying RT method, are accurate in regularly shaped (i.e. quasi-cubic) rooms with uniform absorption. However, the accuracy drops as the room aspect ratio and absorption uniformity decrease (Hodgson 1996). Kuttruff (2000) saw room shape as a non-critical factor in determining reverberation. However, he also mentioned that room shape influences strongly the

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number, directions, delays and strength of the early reflections. Therefore, room shape can be important in determining the Early Decay Time (EDT).

Reverberation Time Measurement Suggested by International Standard (ISO)

According to ISO 3382 (1997), RT can be measured from T30. The sound source for RT measurement should be as close to omni-directional as possible and should produce sufficient sound energy to provide a decay curve that is not affected by background noise. For this, a sound source that is at least 45 dB above the background noise level source is required. The microphone should be as small as possible, with diameters up to 26mm allowed. The minimum distance between the microphone and the nearest reflecting surface, including the floor, should be at least a quarter of a wavelength, normally around 1m for measurements in one-third-octave bands from 100 Hz to 5 kHz. Octave bands from 63 Hz to 4 kHz can be measured in concert halls and rooms for speech. ISO recommends a minimum distance $d_{\min} = 2\sqrt{V/cT}$, where V is the volume, in cubic meters; c is the speed of sound, in meters per seconds; and T is an estimate of reverberation in seconds for measurement to occur in the far field. At least two source positions, representing sound source locations, should be used and the average of three or four microphone positions, representing the audience seating area, should be used for RT measurements. Preferred reverberation time measurement frequencies are octave bands from 63 Hz to 4 kHz in concert halls and rooms for speech. A single number reverberation time can be measured from the average of T_{30} in 500 Hz and 1000 Hz octave bands. During RT measurement, the height of the microphone above the floor should be 1.2 meters, which corresponds to the ear height of the average listener in a typical chair (ISO, 1997).

Speech Perception Measurement

The degree of speech understanding by a listener can be measured by recording the percentage of speech units correctly perceived by listeners. The degree of speech understanding is measured in articulation or intelligibility (Harris 1998).

Table 2-6. Summary of subjective and objective speech perception measurement methods

Assessment Categories	Measurement Methods	Basis	Merit	Problems
Subjective	• Phonetically Balanced Word Scores (PB-word scores) • Rhyme Test • Modified Rhyme Test (MRT) • Sentence Tests • Articulation Loss of Consonant (AL_{cons})	Use speakers and listener	Measure actual human perception	• Time and space limitation. • Repeatability problems
Objective	• Useful-to-Detrimental Sound Ratio (R_{sn}) • Simplified Useful-to-Detrimental Sound Ratio (U_{80}) • Articulation Index (AI) • Speech Transmission Index (STI) • Rapid Speech Transmission Index (RSTI) • Articulation Loss of Consonant (AL_{cons})	Use physical parameters of target space	Predict speech perception through certain models	Can be an indicator of, but not a direct measure of actual perception by people because people were not involved in the measurements

A number of methods have been developed to assess speech perception. These methods can be categorized into two principally different assessment methods: subjective and objective measurement method (Table 2-6). The basis of subjective measurements is the relationship between speakers and listeners (the amount of correctly recognized speech items by the listener is measured). The primary advantage of this method is that it measures actual human perception. However, drawbacks such as the difficulty to perform the tests due to time and space limitations or difficulty of replication of the same results can be expected. Objective measurement (also called quantitative method) is based on the physical parameters of a testing space. Measured parameters are used in predicting speech perception through certain models (Steeneken 2002).

Subjective Perception Assessment

Speech perception is measured by the number of speech items that are recognized correctly. Various types of phonemes, words (meaningful or nonsense words), or sentences can be used in speech perception measurements. Generally, the detection of meaningful words is easier than that of nonsense words. When words are used, test words are embedded in a carrier phrase. Open or closed responses are available in these tests. In open response cases, test subjects are expected to respond to what they heard. Alternative selections for answers are given in closed response cases. According to Logan and colleagues' study (1989), using the open response format showed as much as a 41 % greater error rate than the closed response format. The following paragraph provides examples of subjective measurement methods.

Phonetically balanced word scores

The Harvard PB-Word score measures the "intelligibility of speech" by counting the number of discrete speech units correctly recorded by the listener in a test. The PB series consists of 20 lists. Each list was designed to satisfy following requirements: monosyllabic structure; equal average difficulty; equal range of difficulty; equal phonetic composition; a composition representative of English speech; and words in common use.

Each list contains 50 monosyllables. The range of difficulty of those monosyllables is wide enough to make them adequate for most types of speech intelligibility comparison and each list has same spread of difficulty and average difficulty. During a test each word is read within a carrier sentence and the listener is required to record the word they heard. Test results are analyzed through statistical procedures to eliminate unexpected errors (Egan, 1948). This test method is relatively difficult to administer because of the large number (1000) of response alternatives (Kryter and Whitman 1965).

Rhyme test

The words in the rhyme tests are more difficult than the words used in the PB test. The listeners cannot get multiple linguistic and acoustic cues which are available in the PB test. The only acoustic information given to the listener is contained in the initial consonant of the test word. However, this test is easy to administer because of the limited number of selections for each test word, about 8-9 alternatives (Fairbanks 1958; Kryter and Whitman 1965).

Modified rhyme test (MRT)

In the MRT test, 50 wordlists consisting of 6 American English monosyllabic words are used for the speech intelligibility test and its results can be expressed as the number of words heard correctly. Words are constructed in consonant-vowel-consonant form with different initial and final consonants. The same vowel is used in all six lists. Test subjects are asked to select similar words spoken by the speaker from the six-word lists.

Generally this method is similar to the Fairbanks' Rhyme test. However, it is different in the constraints imposed upon the words. The six equivalent word lists are not phonetically balanced and the strict orthographic constraints are not imposed as required by Fairbanks' answer form. During the test, the listener will be provided with a closed set of six alternatives to select his or her identification of the message. This eliminates the usual required learning time in testing procedures to gain familiarity with the test material (House, Williams, Hecker, and Kryter 1965).

Sentence tests

Sentences can also be used to evaluate the comprehension of speech. Carefully selected sentences that reflect the occurrence of words in language are used in this test method. Harvard psychoacoustic sentences use a closed set of 100 sentences to test intelligibility. This test can be easily performed without training the subject. However, because of meaning, context, rhythm, etc., missed items during the test can be assumed from context. The influence of these factors on test scores makes the results difficult to analyze and interpret (Egan, 1948). The fixed set of sentences can cause learning effect problems when the test is repeated (Pisoni et al. 1980; Kleijn et al. 1998). Haskins Semantically Anomalous Sentences (HSAS) are also used to measure speech intelligibility in sentence form. Unlike Harvard sentences, HSAS uses non-sense sentences to cause difficult perception. Guessing from the meaningful context, which is possible in Harvard psychoacoustic sentences, is not possible in HSAS (Nye and Gaitenby 1974).

Objective Intelligibility Assessment

The basic idea of this method is to explain speech perception by using objective measurement parameters. This method takes into account the room sound reflections, background noise, or both of them. Objective measurement methods have fewer limitations in use than subjective methods. Repeatable and unbiased results, which may not be possible in subjective tests due to human factors, can be achieved from an objective intelligibility assessment. This assessment can be an indicator of, but not a direct measure of actual perception by people because people were not involved in the measurements.

Energy ratio-based speech intelligibility method

One of the early efforts to explain speech perception by an objective parameter, the energy ratio (D50: originally named 'Deutlichkeit'), was done by Thiele (1953). This early-to-total sound energy ratio was used to define an objective criterion of distinctness of sound and it is given by Equation 2-3.

$$D = \frac{\int_0^{50ms} [g(t)]^2 \, dt}{\int_0^{\infty} [g(t)]^2 \, dt} \times 100\% \qquad (2\text{-}3)$$

The early (useful) sound was considered to be the direct and the reflected sound energy that arrived at the receiver position within 0.05 seconds after the direct sound. However, the detrimental effect of background noise was not considered in this method (Thiele 1953; Kutruff 1991).

Lochner and Burger (1964) developed a weighted useful-to-detrimental sound ratio (Equation 2-4). From their experiments, they found that up to 95 msec delayed reflected energies are fully or partially integrated with the direct sound to improve speech intelligibility. Early reflected sounds are integrated with the direct sound according to the fraction α of the echo energy integrated for different levels and delay times relative to the direct sound. From the assumption that the two components, background noise and reverberant speech noise, can be measured separately, the useful-to-detrimental sound ratio was expressed as;

$$R_{sn} = 10\log\left[\frac{\int_{0}^{95}\alpha p^2 dt}{\int_{95}^{\infty} p^2 dt + p_n^2 \Delta t} dB\right] \qquad (2\text{-}4)$$

α: fraction of the echo energy determined by echo levels and the delay time graph
p: instantaneous value of the sound pressure (N/m^2)
p_n: r.m.s. pressure of background noise (N/m^2)
Δt: duration of the pulse used for the measurement (millisecond)

Latham (1979) modified Lochner and Burger's method (Equation 2-5) which considered noise as a steady state with a speech spectrum.

$$S/N' = 10\log\left[\frac{\int_{0}^{95}\alpha_{(p,t)} p_{(f,t)}^2 dt}{\int_{95}^{\infty} p_{(f,t)}^2 dt + p_{PNC}^2 T} dB\right] \qquad (2\text{-}5)$$

f: 1 kHz octave band filter passed recorded impulse response
α: fraction of the echo energy determined by echo levels and delay time graph
p: instantaneous sound pressure (N/m^2)
t: time in milliseconds relative to the arrival of the direct sound
T: the period of the speech intelligibility test-passage
P_{PNC}: equivalent pressure of the mean-maximum (approximately L_{10}) level of ambient background noise specified by PNC curves

In this method transient and spectral characteristics of ambient background noise were considered by the L_{10}PNC level. According to Latham, the temporal characteristics of ambient background noise were considered by using L_{10} and spectral characteristic of background noise was specified by PNC curve. This modified useful-to-detrimental energy sound ratio was applied as design criteria to predict and to successfully evaluate a number of theaters.

$$\mathrm{U}_{80} = 10\log\{C_{80}/(1+(C_{80}+1)\times I_n/I_s)\}, \mathrm{dB} \qquad (2\text{-}6)$$

$$\mathrm{C}_{80} = \int_{0}^{80} \mathrm{p}^2(t)dt \Big/ \int_{0.08}^{\infty} \mathrm{p}^2(t)dt$$

I_n/I_s: ratio of A-weighted steady state background noise and speech intensities.
p: instantaneous value of the sound pressure (N/m^2)

Bradley (1985) developed a simplified version of Lochner and Burger's useful-to-detrimental energy ratio (Equation 2-6). He used simple (un-weighted) sums of the useful (early) speech energy. This method was as accurate as other measurement methods (STI, AL_{cons}). A comparison study (Bradley 1998) showed a strong (R^2>0.95) correlation with other measurement methods.

Articulation index (AI)

The assumption of AI is that the specific information content of a speech signal is not equally distributed in the frequency range of a speech signal. Therefore, speech intelligibility can be measured by summing the contribution of each frequency on overall intelligibility (French and Steinberg 1947). The contribution of each frequency band to the AI is calculated from the difference between an idealized speech spectrum and the noise level: if the difference is smaller than zero then contribution is zero; if the difference is greater then 30 then the contribution is 30. Each contribution is multiplied by a weighting factor (Table 2-7) specific to the particular octave band. The sum of each frequency contribution multiplied by the weighting factor is the AI (ANSI S3.5 1969).

Table 2-7. Articulation index weighting factors

Center Frequency	250Hz	500Hz	1000Hz	2000Hz	4000Hz
Weighting factor	0.0024	0.0048	0.0074	0.0109	0.0078

Speech transmission index (STI)

The Speech Transmission Index method was started in the 1970's at the TNO research laboratory in the Netherlands. The basic idea of this method is conservation of the speech spectra. Speech is a flow of sound with continuous changes over time. Two different spectra can be found in a flow of speech. One is the audible spectrum, the spectrum normally measured with a sound level meter. The audible spectrum of speech occupies a wide range of frequencies from about 100 Hz to 10 kHz, which can be represented by the seven octaves from 125 Hz to 8 kHz. The other spectrum is the modulation spectrum. The sound we hear in speech is organized into phonemes. The modulation spectrum defines the rate at which phonemes are spoken (Houtgast, Steeneken, and Plomp 1980; Jacob 2001; Steeneken 2002). A phoneme is the basic auditory unit of speech. It serves to distinguish between meanings of words, such as the differences among had, head, heed, and hid (Yost 1997). The frequency of phoneme production is much lower than the audible frequency range. The rate at which phonemes are spoken is the modulation spectrum. The modulation spectrum can be represented by fourteen frequencies spaced at one-third octave intervals ranging from 0.63 to 16Hz. When the speech signal is transmitted through an enclosure, its modulation amplitude is important in speech intelligibility. However, this modulation amplitude is deteriorated by noise, reverberation, or other acoustic defects. Reverberation can smear the fast highly peaked envelopes and noise can reduce the absolute signal amplitude level. The difference between the original modulation spectrum and the modulation spectrum changed by noise or reverberation is the Modulation Transfer Function. STI is obtained from the Modulation Transfer Function (m(F)) of an enclosure, and the determination of the effective signal-to-noise ratio of a test signal frequency. The test signal consists of 7 separate octave band signals. A full matrix for seven-octave bands and 14 modulation frequencies (0.63-12.5 Hz) is obtained from the test signal. The effective SNR for each octave band is derived from the matrix. STI is calculated from the weighted summation of the seven octave contributions. Normalization results in the STI range from 0 to 1 (Houtgast, Steeneken, and Plomp 1980; Jacob 2001; Steeneken 2002).

Rapid speech transmission index (RASTI)

Houtgast and Steeneken (1984) developed a simplified version of STI, Rapid STI (RASTI) because of the time demanding and complicated process of STI. RASTI can be measured from four modulation frequencies in the 500 Hz octave band frequency and five modulation frequencies in the 2 kHz octave band frequency. The range of applied modulation frequencies are from 0.7 to 11.2 Hz (Houtgast et al. 1984; Kuttruff 1991). The drawback of this method is the limitation of sound frequency. No information is gathered at low frequency and high frequency areas (Mapp 1997).

Articulation loss of consonant (Al $_{\mathbf{cons}}$)

Through the analysis of errors in the syllable articulation test, the number of errors due to incorrectly perceived vowels was smaller than for consonant and most consonant errors were among final consonants (Peutz,1971). Peutz (1971) used the articulation losses of consonants as the measure of speech intelligibility in rooms. Articulation loss was measured from the relative number of wrongfully perceived phonemes by a group of listeners under various conditions. Based on tests conducted under varying conditions of reverberation, distance to source, and room volume, he found a simple relationship between measured parameters and articulation loss of consonants. On the basis of tests conducted under different conditions without background noise, the Al_{cons} could be expressed by a simple formula (Equation 2-7 and Equation 2-8). A different formula was used depending on the distance between speaker and listener. When the distance between speaker and listener is shorter than the critical distance, $D_c = 0.20\sqrt{V/T}$, articulation loss of consonant can be given by

$$\%Al_{cons} = \left(\frac{200 \cdot (DT)^2}{V} + \alpha \right)\% \qquad (2\text{-}7)$$

T=reverberation time (for 1400Hz) (second)
V=Volume of room (m^3)
D=distance source to listener (meter)

When distance is longer than D_c, articulation loss of consonant is

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$\%AL_{con}=(9T + \alpha)\ \%$ (2-8)
T=reverberation time (for 1400Hz) (second)
α=correction for degree of listener, vary between 1.5 to 12.5% for different listeners

Because this method was developed from subjective test results and objective factors, this also can be one of the subjective measurement methods. The drawback of this method is limited usage of sound source components. The measurement is taken in only one frequency band (Templeton, Sacre, Mapp, and Saunders 1993).

Effects of Acoustical Variables on Speech Perception

Overview of Effects of Reverberation on Speech Perception

In general, speech perception decreases as reverberation increases (Locher and Burger 1964; Nabelek and Pickett 1974; Finitzo-Heiber and Tillman 1978; Houtgast 1981). Excessive reverberant sound energy causes spectrum overlaps and smears the clear sound spectra. Vowels, which have more sound energy and longer duration than consonants can overlap the consonants which have more acoustic information by extended reverberation (Knudsen 1932; Puetz 1971; Pearsons et al. 1982). Houtgast and colleagues' (1980) saw the effects of reverberation on speech perception in different aspects. They claimed that when the speech signal is transmitted through an enclosure, its amplitude modulation contains important information than the carrier and amplitude modulation can be easily deteriorated by excessive reverberation. Deterioration of speech perception due to reverberation becomes more serious to the listener with hearing loss problems (Finitzo-Hieber and Tillman 1978; Bradley 1985; Crandell 1991).

Previous Reverberation Studies

Nabelek and Robinson (1982) tested both monaural and binaural speech perception in 3 different reverberation conditions, 0.4 seconds (small room), 0.8 seconds (medium size room or conference room), and 1.2 seconds (large listening areas like assembly halls, church, and drama theaters), for 6 groups of listeners at various ages. Through their tests they found a significant (with a 0.01 significance level) deterioration effect of reverberation on speech hearing. They also found a significant interaction of age and reverberation on speech hearing (*p*=0.0561). The young adults performed significantly better than the young and old groups in all conditions, but the young adults were still affected by longer reverberation. The means of speech recognition for RT of 0.8 and 1.2 seconds were not significantly different but were different from the mean of 0.4 seconds (with 0.01 significance level). Regardless of age and RT condition, the binaural condition showed 5% better speech intelligibility than the monaural condition.

Finitzo-Hieber and Tillman (1978) tested the effects of reverberation on normal hearing and hearing-impaired subjects using simulated conditions in educational environments. Three different reverberation conditions, 0.0, 0.4, and 1.2 sec of average RT in the 500 Hz, 1 kHz, 2 kHz, were used with a babble of eight talkers as a background noise. This study showed that reverberation has a deteriorating effect on speech intelligibility for both normal and hearing-impaired subjects (*p*<0.01). For the normal-hearing group, an average of 7 intelligibility scores were decreased from reverberation time change from 0 to 0.4 seconds. Meanwhile, an average of 16 intelligibility scores were reduced when reverberation time changed from 0.4 to 1.2 seconds. A larger intelligibility score reduction was measured from a hearing impaired group. An average 9 and 19 intelligibility score reductions were identified from reverberation time changes from 0 to 0.4 seconds and from 0.4 to 1.2 seconds. It also showed that the combination of noise and reverberation showed stronger effects on speech perception than the summation of individual effects of noise and reverberation (*p*=0.004). This implies that people with hearing impairments can experience more severe hearing problems under reverberant conditions than normal hearing people in the same condition ($p<0.001$).

Houtgast, Steeneken, and Plomp (1980) used the Speech Transmission Index (STI) to predict optimum reverberation times under different noise conditions. The STI increased monotonically from 0.9 to 0.2 with decreasing reverberation under no interfering noise conditions and a maximum STI of 0.9 is acquired under very low reverberant (about 0.1 seconds) conditions. However, the presence of noise resulted in a broad maximum STI. The maximum STI shifted towards longer reverberation times for higher noise levels. As the level of interfering noise increased from 40 to 60 dB, the optimum length of reverberation time increased from 0.3 to 2 seconds.

Bradley (1985) used an energy based speech perception measurement method, U_{80} (Equation 2-6), to find the required reverberation times for optimum speech perception. According to Bradley's definition, the optimum speech perception was 100% speech understanding or the point where the mean trend showed no further increase in speech perception scores. From the relationship between U_{80} and speech perception, a U_{80} value of 4.0 dB at 1 kHz was found as the optimum value for excellent (99% speech intelligibility) conditions for speech. In order to achieve 4.0 dB of U_{80} at 1 kHz, short reverberation (0.2 seconds) was required for a low signal-to-noise ratio (10 dBA) condition, and longer reverberation (0.85 seconds) is demanded for higher signal-to-noise (25 dBA) conditions.

Overview of Effects of Noise on Speech Intelligibility

Any disagreeable or undesired auditory stimuli are noise (Harris 1998) and noise interferes with students' hearing and understanding (Crandell et al. 1995). In addition to reverberation, noise is another factor that reduces speech perception. Both the loudness and spectral characteristics of noise can affect speech perception. The deterioration of speech perception by noise can be more significant under extended reverberation conditions than limited reverberation conditions and persons with hearing disabilities can be impacted more than normal hearing persons (Finitzo-Hieber and Tillman 1978).

Previous Noise Studies

Knudsen (1978) suggested a 65 dB level of source loudness for good speech perception for average listeners in a reasonably quiet condition (40 dB). However, in the presence of competing or masking noise (Yost 1997; Gelfand 1998), additional source loudness is required to provide similar speech perception to that which was achieved under no noise conditions. The sensorineural cells which normally respond to the source sound do not respond because they are occupied with responding to the noise (Kryter 1994). Effects of competing noise on hearing can be categorized into 3 groups: temporary threshold shift; permanent threshold shift; and acoustic trauma (Burns 1973). Temporary threshold shift is defined as a short term hearing level elevation by an exposure to noise and the elevation of the hearing level is reversible. When the limit of exposure compatible with recovery is exceeded, recovery from the temporary threshold shift will not proceed and lead to permanent threshold shift. At this condition, no possibility of further recovery is expected. Acoustic trauma is a condition of sudden aural damage from short term intense exposure. Even a single exposure to explosive pressure rises can cause acoustic trauma (Ward and Glorig 1961). Both source and noise levels should be considered together for actual speech perception. The relationship of speech and noise levels on speech perception was shown through Lochner and Burger's (1964) study. According to their study, the increase of signal-to-noise ratio provided an improvement in speech perception. An interesting point from their study was that higher source levels did not always mean higher speech intelligibility. A maximum intelligibility of speech could be obtained at a speech level in the vicinity of 60 dB. After that point, actual speech intelligibility decreased with higher source loudness. For people with hearing impairments, speech perception decreased after speech level reached a certain critical level (Mcfarland 1999). This phenomenon can be explained by the relationship between frequency components and associated sound energy and this will be discussed later.

ANSI S 12.60 (2002) recommended 15 dB signal-to-noise ratio to ensure good speech perception based on several factors (an addition of 2 dB for neurological immaturity compensation, an additional 5 dB for sensorineural and conductive hearing losses, an additional 5 dB for limited English proficiency and language disorders, and an additional 3 dB for excessive reverberation). The American Speech-Language-Hearing Association (ASHA) and multiple authors also recommend a 15 dB signal-to-noise ratio to provide preferred speech perception for children with hearing impairments and language disabilities (Houtgast 1981; Bradley 1986; ASHA 1995; Crandell and Smaldino 2000). According to Bradley's study (1986), 100% speech perception can be achieved under this signal-to-noise condition with 0.5 seconds reverberation.

Both listeners and speakers can be affected by noise. Speakers continuously monitor their voice levels during speaking. When speakers feel that their voice levels are relatively low compared to the "normal" speech level, they will increase them. The opposite case also happens. Therefore, if speakers and receivers are not exposed to the same noise condition, problems can occur. For example, when speakers are exposed to quieter noise conditions than receivers, the speakers will not generate enough sound energy, which is required at the receivers' locations. As a result the receivers are not able to achieve proper speech perception due to both a low source level and a loud background noise level. Similar situations can be found inside classrooms. Many noise sources such as the HVAC system, projector(s), or students' activities can be found inside classroom. During most speech perception experiments, a reverberant sound field is assumed. Under the reverberant sound field assumption, all test subjects within a test room are assumed to be exposed to the same background noise level. However, in many cases of real classroom conditions, noise sources are located closer to students than teachers. As a result, students are exposed to higher noise levels than teachers, who are trying to adjust their voice levels according to the noise level at their locations. Hodgson (1996) mentioned that each student is exposed to different noise levels depending on the noise source-listener distance and room conditions such as room geometry, wall diffusion, and absorption. The change of the speech level by the background noise level was measured. Heusden et al. (1979) found that speech levels increased about 3 dB for a 10 dB rise in noise level. This increment was smaller than what Pearsons and colleagues (1977) suggested. They suggested a voice-level-increment rate of 1 dB/dB_{noise} in background noise that ranged from 45 to 55 dB.

In addition to the loudness of the sound source and competing noise, the spectral characteristics of the sound source and noise should be considered to secure clear communication. The importance of the speech spectrum on speech perception has been studied by many researchers. French and Steinberg (1947) showed the effect of spectral information of the sound source in speech perception. According to their study, sound source information between frequencies of 1000 Hz to 3300 Hz resulted in a 60 % change in speech perception. A similar study was performed by Hirsch, Reynolds, and

Joseph in 1955. In their study, they used band-pass filters to test the effect of speech spectrum on speech perception. This study showed the importance of sound sources at mid and high frequencies for speech intelligibility. Articulation Index (AI) clearly shows the importance of source spectrum in speech perception. Sound information at high and mid frequencies, where most consonants are located (French and Steinberg 1947; Knudsen 1932), give 2 times or more contributions than low frequencies to the speech perception (ANSI S3.5 1969).

In spite of its importance as the primary speech information carrier, mid and high frequency-sounds do not have strong energy. Instead, most sound energy is located in the lower frequencies. As a result, mid and high frequency sounds can be easily overpowered by relatively less important low frequency sound (Fletcher 1953). The less important low frequency sounds (i.e., vowels) will overpower the important information-carrying mid and high frequency sounds (i.e., consonants) and this will increase at higher overall listening levels and cause poorer speech perception (Moore 1977). Under reverberant condition this phenomenon becomes more serious (Fletcher 1953).

In addition to speech perception reduction by the spectral characteristics of the sound source, a sound source can also be distorted by the spectral characteristics of noise sources. Ehmer's study (1959 b) used pure tones and noise bands to measure the effects of competing noise on hearing. From his study, both narrow band noise and pure tone showed strong masking at the noise frequency. In addition, narrow band noise showed smoother masking patterns, more masking at the vicinity of the center frequency of the masker than found from pure tones. A similar result was found from Wightman and colleagues' (1977) study. Small amounts of noise energy were required to mask spectrally similar sound sources, but more noise energy was required to mask spectrally different sound sources.

A masking pattern of masker frequency changes according to the noise level. As found from the results of Ehmer (1959 b) and Causse and Chavasse (1947), the maximum threshold shift occurred at the exposed frequency with a symmetric pattern under a low-level (60 dB) condition. However, as the noise level increases the masking pattern becomes asymmetrically wider and more masking occurs at frequencies higher than the masking frequency (called the upward spread of masking) (Hawkins and Stevens 1950; Ehmer 1959; Small 1959; Fink 1961; Gelfand 1998). Davis and colleague's study (1950) found that maximum threshold shifts occur as a frequency about one half, or more of an octave above the frequency of the exposure tone or noise frequency band. This was confirmed by Hirsh and Bilger study (1955). According to their study, the temporary threshold shifts from noise tones of 1000 and 2000 Hz were greater at 1400 and 2800 Hz respectively than 1000 and 2000 Hz under a high level of stimulation.

Miller's (1947) study showed different masking by spectrally different masking noises. According to his study, a wide-band masking noise was the most effective in masking speech. When narrow band noise was used, higher frequency noises masked more than low frequency noises at low noise level condition (S/N>0 dB). However, low frequency noises masked more than high frequency noises at high noise level condition (S/N<0 dB).

The content of noise is also needed to be considered for speech perception. More masking happens by noise with linguistic information than non-linguistic noise. babbling noise from multiple sources with linguistic content has stronger masking effects than an equally intense electronically generated noise with the spectral characteristics of long-term speech. This phenomenon is called perceptual masking (Carhart et al. 1969; Elliot et al. 1979). According to Carhart et al. (1969), 3.2 dB over-masking (perceptual masking) occurred in the presence of speech as the noise source.

Noise-Induced Annoyance

Annoyance is the subjective impression of unwantedness of noise (Kryter 1985). Noise-induced annoyance is not a simple and immediate sensation like loudness (Fidell and Green 1998). Annoyance is not decided by absolute noise level alone. Both acoustic and nonacoustic factors have effects on annoyance (Shepherd 1987). The measurable acoustic factors are sound level, frequency spectrum, duration, spectral complexity, and fluctuation in sound level. Personal perceptions are considered as nonacoustic factors (Molino 1979). Table 2-8 shows the factors that affect annoyance induced by noise.

Table 2-8. Factors that affect annoyance (Molino 1979)

Types		Factors
Acoustic Factors	Primary	Sound level
		Frequency
		Duration
	Secondary	Spectral complexity
		Fluctuation in sound level
Nonacoustic Factors		Adaptation and past experience
		Listeners' activity
		Predictability
		Individual difference and personality

Noise level is the most distinctively measurable acoustic factor that has a strong effect on annoyance. When noises have similar spectra and duration, annoyance is strongly related with noise level (Molino 1979; Kryter 1985). However, when there a is wide difference in noise spectra or duration, annoyance is not directly related to loudness (Molino 1979). In general, higher frequency noises cause more annoyance than low frequency noises at the same noise levels (Kryter 1985). For continuous narrow bandwidth noise of moderate noise level (40 to 80 dB), frequencies in the region of 2,000 Hz to 8,000 Hz are usually the most annoying. Sounds with frequencies below 500 Hz and above 10,000 Hz are less annoying for the same loudness condition than noise between 2,000 Hz and 8,000 Hz (Molino 1979; Kryter and Pearsons 1963). The duration of noise is another factor affecting annoyance. Noises of longer duration usually cause more annoyance than shorter duration noise (Kryter 1963). However, when the noise level fluctuates, noises with shorter durations can cause more annoyance than long duration noise with a constant noise level (Molino 1979). The annoyance attributed to steady-state noise is determined by the total noise level, whereas the annoyance of intermittent noise is determined by the rate of intermittency as well as the noise level (Wilshire 1987). Noise with energy concentrated in narrow bands usually causes more annoyance than broad-band noise with energy equally distributed over frequencies (Kryter 1985). When noise with a relatively flat random noise spectrum is combined with pure tones, more loudness and annoyance would be measured than would be predicted from the basis of the sound level of their combination (Molino 1979). The degree of annoyance can be affected by individual experience. If an individual has been exposed to the same noise, the individual can tolerate the noise and be less annoyed by the previously experienced noise. If a noise is related with unpleasant or annoying events, the noise may become more annoying. An individual's activity can affect annoyance. When an individual is involved with noise tolerating activities such as exercising, noise causes less annoyance than when the individual is involved with noise sensitive activities such as reading or sleeping. Noises that occurring randomly and unpredictably cause more annoyance than noises which occur at predictable and periodic intervals. A wide variation can be found in the threshold of annoyance for different individuals. Generally, extroverts have higher noise annoyance tolerance than introverts (Molino 1979).

Annoyance can be measured using surveys. Generally, four fundamentally different methods are used: verbal rating scales; numerical rating scales; multiple-item indices; and ranking scales. In verbal rating scales, a limited number of words which define degree of annoyance are presented to respondents to express their annoyance. Different types of verbal rating scales (differ in the question that is used and the number of words from which the respondent can choose) are available. The most commonly used method is the "Single Verbal 4-Points Scale" (Fields 1994). In this method, a single question with four alternatives is asked to respondents to describe their degree of annoyance. In the numeric scale method, respondents are expected to express their degree of annoyance by choosing a number from a series of numbers with assigned verbal labels at the end points of a scale. As a combined form of verbal rating scales and numerical rating scales, a scale based on verbal categories (Molino 1979) is also used in surveys (Diamond and Rice 1987; Gabrielsson et al. 1990). In the multi-item index method, numerical values are assigned to answers on each of several questions and an overall index score is computed by combining scores from constituent questions. It is not possible to find out how the respondents answered each question from the composite score. In the ranking scale, respondents are asked to rank series of choices. Using this method, respondents are able to express their opinion regarding various issues within choices (Fields 1994).

Hypothesis and Proposed Model

The effects of noise and reverberation on speech perception are clearly shown in the literature. There are many factors affecting speech perception in addition to the loudness of noise. Speech perception was changed by various noise-related factors such as noise spectral characteristics, content of noise, noise-induced annoyance, and others. Therefore, in order to understand speech perception within classrooms, not only noise level and reverberation time but other noise-related factors should also be considered.

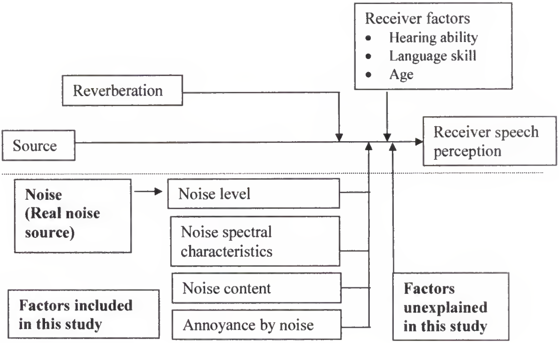

Receiver factors
Hearing ability
Language skill
Age
Reverberation
Source
Receiver speech perception
Noise (Real noise source)
Noise level
Noise spectral characteristics
Noise content
Annoyance by noise
Factors included in this study
Factors unexplained in this study

Figure 2-3. Speech perception model

Based on the previous discussion, a speech perception model including the effects of noise related factors is proposed in Figure 2-3. The key in this model is the consideration of noise-related factors measured from actual classroom noise sources. The effects of previously studied factors on speech perception were tested in this study using actual noise sources found within classrooms. This will help to get more actual speech perception within classrooms because actual noise sources that students are exposed to within classrooms were used and more parameters were used in explaining speech perception.

CHAPTER 3
METHOD

Research Design Overview

Studies were designed to measure the characteristics of classroom noises and to test the effects of those noise characteristics on speech perception. For these purposes, three different types of measurements were taken: measurements using a computer simulation; measurements within classrooms; and measurements using human subjects.

As a pilot study, a computer simulation was used to measure the effects of spectrally different noises on speech perception. The STI (Houtgast, Steeneken, and Plomp 1980) was used as a measure of speech perception. Four spectrally different noises based on the ASHRAE Application Handbook (1999) and Lilly (1999) study which could be expected within classrooms were used as background noise. The four spectrally different noises: 1. noise with strong high frequency components (SHC); 2. noise with strong high and low frequency components (SHLC); 3. noise with strong low frequency components (SLC); and 4.noise with strong mid frequency components (SMC) were tested over five different noise levels, 35 dBA, 45 dBA, 55 dBA, 65 dBA, and 75 dBA.

Classroom noise was profiled through field measurements in 41 classrooms in 7 Alachua County elementary schools in Florida. A total of 135 measurements were taken of the levels and spectral characteristics of noises within classrooms. Eighty two measurements were taken in the students' seating areas close to a noise source and 53 were made at noise source locations. The effects of spectrally different noises taken from classrooms on speech perception were measured using a subjective speech perception measurement method, the Modified Rhyme Test (MRT) (House, Williams, Hecker, and Kryter 1965). Thirteen voluntary research participants took the MRT test. Two spectrally different noises, recorded using a digital recorder from the field measurements were used as background noise during the MRT tests. The results of the MRT tests were statistically analyzed to measure effects of the noise related parameters on speech perception.

Simulation Test

The effects of spectrally different noises on speech perception were measured using a computer simulation, using CATT Acoustic v8.0 software. Two existing classrooms, Dauer Hall 68 and 342, located in the Department of Communication Sciences and Disorders building at the University of Florida campus, were simulated and speech perception was measured using STI. Each room has acoustically different conditions. Dauer Hall 68 has 41 seats and is mostly used for mid-size classes. Acoustical ceiling tiles were used for the ceiling. The wall surfaces were finished using painted gypsum-board and painted concrete masonry units (CMU). Forty percent of the west-side wall was treated with acoustic wall panels. For maintenance purposes, vinyl tiles were used for the floor. The average reverberation time of this room at mid-frequencies (500, 1000, and 2000 Hz) was 0.57 seconds. The simulated room dimensions are shown in Table 3-1 and the average room absorption ($\overline{\alpha}$) in each frequency is summarized in Table 3-2. Dauer Hall 342 is a smaller room with 20 seats and is mainly used for small classes. In general, this room was finished using hard surface materials. The walls and ceiling were finished using painted gypsum-board and painted CMU wall. Vinyl tiles were used as the floor finish. This room has a mid-frequency reverberation time of 1.21 sec.

A raised voice level of 65dBA at 1 meter was used as the sound source.

Table 3-1. Physical dimension of simulated rooms

Room	Length (m)	Width (m)	Height (m)	Volume (m^3)
Dauer Hall 68	8.8	5.1	2.3	103
Dauer Hall 342	5.7	4.9	2.5	70

Table 3-2. Global data of material, source, and RT of simulated rooms

		125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Source Sound Level (65dBA)		54	60	64	59	54	50
Hall 68	Reverberation Time	0.47	0.69	0.63	0.57	0.52	0.49
	Absorption $\overline{\alpha}$	0.16	0.12	0.14	0.17	0.21	0.20
Hall 342	Reverberation Time	0.44	0.92	1.23	1.34	1.05	0.92
	Absorption $\overline{\alpha}$	0.18	0.09	0.07	0.06	0.08	0.08

Three dimensional drawings of Dauer Hall 68 and Dauer Hall 342 showing the seating arrangement and the locations of the source and receivers are shown in Figures 3-1 and 3-2. The acoustic environments within the classrooms were changed by generating background noises. On the basis of the ASHRAE Applications Handbook (1999) and Lilly (1999), four spectrally different noises were configured. These noises included a diffuser noise which has strong high frequency components (SHC), a complex noise of a fan and a diffuser having strong low and high frequency components (SHLC), a noise with strong low frequency components (SLC) which is similar to duct-borne fan noise, breakout noises from the low pressure duct work in classrooms, and finally noise from students' activity which has strong mid frequency components (SMC). All four noise spectra are possibly found within classrooms.

The four spectrally different noises were tested over five different noise levels, 35 dBA, 45 dBA, 55 dBA, 65 dBA, and 75 dBA. The minimum noise level of 35 dBA was chosen to comply with the new ANSI recommendation and the maximum level of 75 dBA was chosen from the highest classroom noise level measured in previous studies

(Pearsons et at. 1977; Houtgast 1981; Markides 1986; Pekkarinen and Viljanen 1991; Hodgson et al. 1999; Siebein et al. 2000).

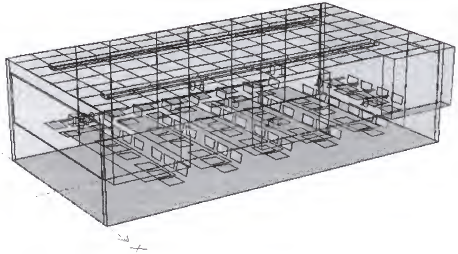


Figure 3-1. Computer model of Dauer Hall 68

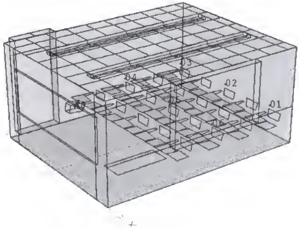


Figure 3-2. Computer model of Dauer Hall 342

Figure 3-3 shows the four spectrally different background noises maintaining the overall noise level of 45 dBA. Noise level differences between dBA and dBC were always less than 20 dB at all noise levels required by the new ANSI standard. Table 3-3 shows the summary of background noise levels used for the simulation study.

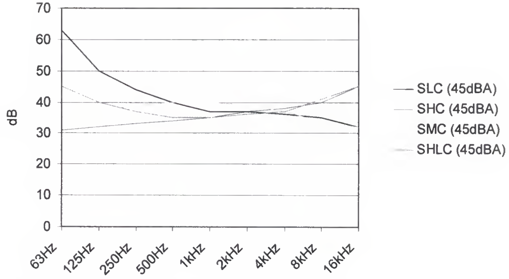


Figure 3-3. Four spectrally different 45dBA background noises

Table 3-3 Summary of background noise levels used in the computer model studies

SPL	Noise Type	Octave Band Center frequency (Hz) 63	125	250	500	1k	2k	4k	8k	16k
35 dBA	SLC	45	40	34	30	28	27	26	25	23
	SHC	21	22	23	24	25	27	28	30	35
	SMC	25	27	29	30	30	29	27	24	22
	SHLC	35	30	27	25	25	26	28	31	35
45 dBA	SLC	63	50	44	40	37	37	36	35	32
	SHC	31	32	33	34	35	37	38	40	45
	SMC	35	37	39	40	40	39	37	34	32
	SHLC	45	40	37	35	35	36	37	41	45
55 dBA	SLC	73	60	54	50	47	47	46	45	43
	SHC	41	42	43	44	45	47	48	50	55
	SMC	45	47	49	50	50	49	47	44	42
	SHLC	55	50	47	45	45	46	47	51	55
65 dBA	SLC	83	70	64	60	57	57	56	55	53
	SHC	51	52	53	54	55	57	58	60	65
	SMC	55	57	59	60	60	59	57	54	52
	SHLC	65	60	57	55	55	56	57	62	65
75 dBA	SLC	93	80	74	70	67	67	66	65	63
	SHC	61	62	63	64	65	67	68	70	75
	SMC	65	67	69	70	70	69	67	64	62
	SHLC	75	70	67	66	65	65	67	72	75

Noise Profiling

A random selection was made of 11 public elementary schools from 22 Alachua County School District schools in Florida. Research applications were sent to the 11 schools through the Alachua County School Board. Seven schools agreed to participate in the study. Measurement trips to the schools were made between November 12, 2003 and November 21, 2003 according to an arranged schedule. Measurements were made during non-class periods as well as during normal class periods. A total of forty one classrooms were visited. Acoustical measurements were taken of various noise sources within the classrooms. A total of 135 measurements were taken. Eighty two measurements were taken in the students' seating area close to a noise source and 53 were made at noise source locations. Table 3-4 shows the summary of nose profiling study.

Table 3-4. Summary of noise profiling study

Study location	Alachua County, Florida
Number of observed schools	7
Number of observed classrooms	41
Number of sound measurements	At source locations : 53 At students' seating area : 82

The A-frequency weighting method, which is most commonly used in sound measurement and used in the ANSI standard, was used during the noise measurements. A Rion NA-27 real time analyzer with a ½" (12.7 millimeter) diameter pre-polarized condenser microphone UC-53A and preamplifier NH-20 were used for measurements. The Rion NA-27 is a hand held unit that can analyze sound levels in 1/1-octave and 1/3-octave bands in real time. The analyzer was calibrated using a Rion NC-72 pistonphone, generating a 114dB internal sine wave at 250Hz, before and after each measurement session. Calibration was within ±0.2 dB throughout the measurement sessions. This instrument meets ANSI specifications for a Type I sound level meter. Measurement data were stored in the memory blocks of the Rion NA-27 and downloaded to computers for analysis. The microphone was located at a seated person's ear height, 4' (1.2 meter) above the finished floor in selected students' seating areas which were close to the noise sources. These locations were selected because speech intelligibility at these locations will be most susceptible to the noise source. Windows in the classrooms were closed during measurements as they would be during normal classroom activities. As a result, interference by outdoor noise was not significant. Measurements were carefully taken not to interfere normal class activities. In parallel with noise level and spectra measurements, noise sources were also recorded using a Sennheiser MKE2 microphone and a TCD-D8 SONY digital audio tape recorder. The following guidelines were applied during measurements and recordings.

- When the occurrence of noises was controllable, a single noise source was measured. During single-noise source measurements, other sources were controlled or turned off, to eliminate or minimize their effects on the measurements. For example, the Air-conditioning system (AC) was turned off for exhaust fan noise measurements; the AC was turned off for overhead projector (OHP) noise measurements, and so on.
- Combinations of controllable noise sources were used to determine the effects of multiple noise sources. For example, AC and OHP were both turned on to measure a combined noise level in the student seating area; the AC was turned on and the water faucet was turned on to measure the combined noise, and others.
- When uncontrollable multiple noise sources were found, the loudest source was considered as the main noise source. No difficulties were found in classifying noise sources due to the clear distinctions in noise levels and characteristics among classroom noise sources.
- When multiple noise sources had equal loudness or were equally audible, all noise sources were considered as main noise sources.

- When there were multiple noise sources in which it was difficult to identify the main source, it was considered as a mixed noise source.
- Silent intervals were not included during measurements.

In addition to sound measurements and recordings, teachers' opinions regarding acoustics in their classrooms were asked. The measured classroom noise data was analyzed using the SPSS statistical analysis program.

Human Subject Test

The effects of spectrally different classroom noises on speech perception were measured in Dauer Hall room 68 located in the Department of Communication Science and Disorders at the University of Florida. The average reverberation time in the mid-frequencies was measured at 0.57 seconds. Figure 3-4 shows the test room arrangement.

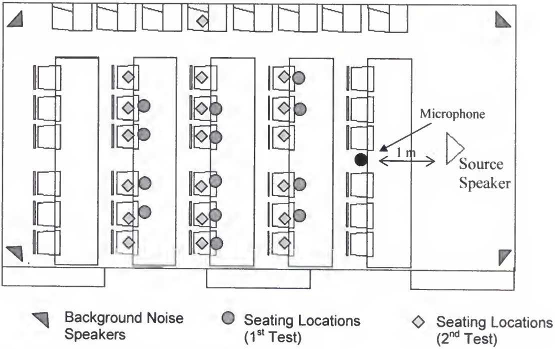

Microphone
1 m
Source Speaker
◥ Background Noise Speakers
● Seating Locations (1st Test)
◇ Seating Locations (2nd Test)

Figure 3-4 Speech perception test room arrangement

The Native English speaking research participants varied in age from 21 to 34 years old. The first test was done using thirteen research participants using 45, 55, and 65 dBA background noise conditions. They included ten university students, two acoustic consultants, and one middle school teacher (average 25.5 year old). An additional test was made using 19 university students over 65 and 75 dBA background noise conditions (average 21.4 year old). Each research participant had undergone a hearing test before the speech perception test. No participants in the study had hearing problems. Only a few minutes of instruction were given to the research participants before the test, because of the simple test procedure.

The Modified Rhyme Test (MRT) was used to measure the speech perception of research participants under different noise conditions because of the convenience in administration using untrained listeners, stable scores, and reduction of any effects of familiarity of test words. This test was designed to evaluate the intelligibility of single initial and final consonants (House, Williams, Hecker, and Kryter 1965). For this study, one session of the test had twenty-five sets of test questions, consisting of six meaningful Consonant-Vowel-Consonant (CVC) words. The research participants were asked to select the identified word from among six meaningful choices, differing either in the initial or the final consonant.

After each session, the research participants were asked to rate their annoyance by the background noise applied during the test. A scale based on verbal categories, a combined form of verbal rating scales and numerical rating scales (Molino 1979; Diamond and Rice 1987; Gabrielsson et al. 1990) was used for annoyance measurement.

Depending on people's previous experience their reaction to noise sources will be different (Molino 1979). Therefore, some people may be very sensitive to a noise source and this may result in a high level of annoyance while other people show a low level of annoyance to the same noise sources. In addition, there is no guarantee of people's use of full range of measurement scales without proper instruction (i.e., some people may answer with mainly high scores or some people may do the opposite).

Those problems may cause a large variation in annoyance responses and cause the data to be skewed. With skewed data, correct analyses may be difficult without a larger amount of data (Ott 1993). In order to reduce this large response variation, research participants were asked to decide the degree of their annoyance from a verbal rating scale then further respond using a numerical rating scale. They were asked to choose a number from a series of numbers with four assigned verbal labels, shown in Figure 3-5.

<table>
<tr><td colspan="5">Zero
Annoyance</td><td colspan="5">Maximum
Annoyance</td></tr>
<tr><td colspan="2">Not at all</td><td colspan="3">A little</td><td colspan="3">Moderately</td><td colspan="2">Very much</td></tr>
<tr><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td></tr>
</table>

Aspect that makes you especially dissatisfied during the test: None / Loudness of noise / Noise color / other (   )

Figure 3-5. Annoyance measurement form

A session of test materials were recorded on a CD and the CD was played in the test room from a Sony PCG-GRZ530 notebook computer, amplified via a CREST Audio CC151 amplifier, and a Tannoy System s600 loud speaker. The sound level of the test material was 65 dBA at 1 meter from the loudspeaker. This is the sound level of person's raised voice that one can expect during a regular class session (Pearsons et al. 1977; Bradley 1985). Noise samples recorded from the classrooms were used as interfering background noises. The noise samples recorded on a CD were played using a Sony PCG-

GRZ530 notebook computer, a CREST Audio CC151 amplifier, and a PARASOUND EQ300 equalizer through four KEF Q15 loudspeakers located at the four corners of the test room to approximate a reverberant sound field for the noise. The background noise level of the test room was measured through the microphone installed 1 meter from the source loudspeaker. Figure 3-6 shows the functional diagram of the test equipment.

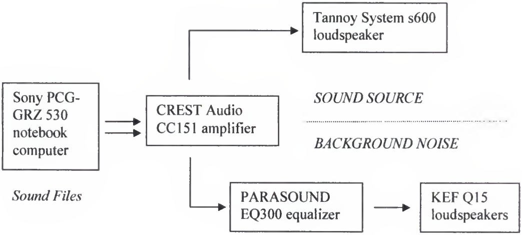

Tannoy System s600 loudspeaker
Sony PCG-GRZ 530 notebook computer
CREST Audio CC151 amplifier
SOUND SOURCE
BACKGROUND NOISE
Sound Files
PARASOUND EQ300 equalizer
KEF Q15 loudspeakers

Figure 3-6. Test equipment functional diagrams

Four different levels of background noise, from 45 dBA to 75 dBA were used. Four different signal-to-noise ratio settings (-10, 0, 10, and 20 dB) were used over 2 spectrally different noise sources of ‘water running (SLHC)’ and ‘HVAC running (SLC)’. Noise levels were measured through the installed microphone. The selection of the 2 noise spectra was described in detail in the ‘Noise profiling study’ section. Spectrally adjusted pink noise which has the spectra of water running and HVAC system noise were also tested.

All sound levels within the test room were measured using the Rion NA-27 real time analyzer with a ½” (12.7 millimeter) diameter pre-polarized condenser microphone UC-53A and preamplifier NH-20. Measurements were made before each test.

CHAPTER 4
MEASUREMENT RESULTS

Computer Simulation Study Results

A computer simulation study was conducted as a pilot to measure noise spectral effects on speech perception. Four spectrally different noises (SHC, SHLC, SLC, and SMC) over five different noise levels (35 dBA, 45 dBA, 55 dBA, 65 dBA, and 75 dBA) were used in the study. The spectral effects on speech-perception scores, measured in STI, are shown in Figure 4-1.

Overall Simulation Results

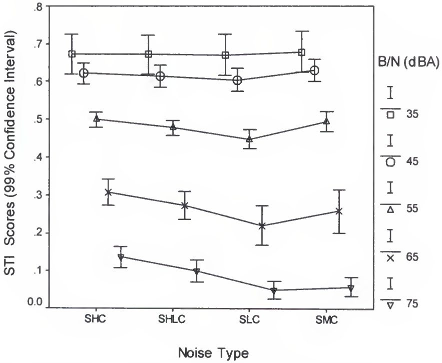


Figure 4-1. Speech Transmission Index (STI) under 4 different noise spectra and 5 different noise levels (both Dauer Hall 342 and 68)

A summary of the simulation data (scores of STI under 4 types of spectra and 5 different noise levels at 12 seating locations in 2 rooms) is shown in Figure 4-1. Generally, STI scores decreased as noise level increased. In addition to the noise level effect on STI scores, Figure 4-1 also shows different STI scores under different noise types. This result shows the effect of spectral characteristics of background noise on STI scores ($df_1=3$, $df_2=220$, $F=13.38$, $p<0.01$). At low background noise levels (35 dBA, 45 dBA), similar STI scores (average 0.67 STI with 0.01 range, 0.62 STI with 0.02 range) were measured over 4 spectrally different noises. However, as the noise level increased (from 55 dBA up to 75 dBA), the noise spectral characteristics' differed the STI scores ($df_1=3$, $df_2=132$, $F=24.2$, $p<0.01$). SLC (noise with a strong low frequency component) showed the greatest decrease in STI scores (dropped to 0.05 of STI points). SMC (noise with strong mid frequency component), which is similar to the speech spectrum, also decreases speech perception (dropped to 0.06 STI). Figure 4-1 shows wide STI score variations. The wide variation might be from room differences: RT of Dauer Hall 68 was 0.57 seconds; RT of Dauer Hall 342 was 1.21 seconds. For further examination of the effect of spectral characteristics of noise on STI scores, reverberation time was controlled. Separate statistical analyses were made for Dauer Hall 342 and Dauer Hall 68, which have different reverberation times. Figure 4-2 shows the simulation data for Dauer Hall 342.

Dauer Hall 342 Simulation Results and Analysis

A total of 120 measurements were taken through 4 different simulations. The effects of noise spectrum on STI scores were measured using 4 different noise spectra over 5 different noise levels. STI scores were measured at 6 seating locations. Figure 4-2 clearly shows the noise level effects on STI scores ($df_1=4$, $df_2=100$, $F=28561.81$, $p<0.01$).

STI score decreased as noise level increased in all 4 noise spectra. In addition to the noise level effect, the noise spectral effect ($df_1=3$, $df_2=100$, $F=268.76$, $p<0.01$) on STI scores is clearly shown in Figure 4-2. STI scores under the same noise level conditions were changed by noise types. The STI scores for the SLC noise test decreased by 0.53 points from 0.61 to 0.08 over the noise level change from 35 dBA to 75 dBA. The STI scores for the SHC noise source decreased the least of all conditions tested. It decreased by 0.45 points from 0.62 to 0.17 as the noise level increased from 35 dBA to 75 dBA.

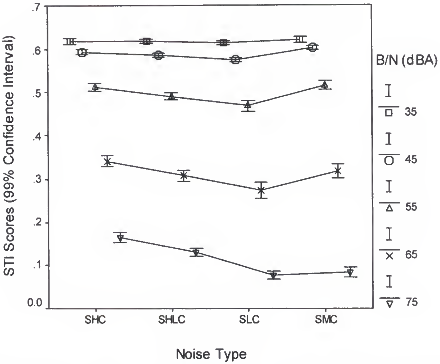


Figure 4-2. Speech Transmission Index (STI) under 4 different noise spectra and 5 different noise levels (Dauer Hall 342)

The noise spectral effect on STI scores changed according to noise level. The STI score changes were between 0.02 and 0.03 under low noise levels (35 dBA and 45 dBA). At these levels, different STI scores (average 0.62 for 35 dBA noise condition and 0.59 STI scores for 45 dBA noise condition) were measured over different noise spectra ($df_1=3$, $df_2=40$, $F=57.46$, $p<0.01$) and the difference was significant at the .05 level.

Strong noise spectral effects ($df_1=3$, $df_2=60$, $F=242.12$, $p<0.01$) were measured at increased noise levels (55 dBA, 65 dBA and 75 dBA). The difference was significant at the .05 level. The change in STI scores under different noise level conditions are shown in Table 4-1. The difference in STI by most interfering noise (SLC) and least interfering noise (SHC) at 75 dBA noise level was about 0.1. The perception from this difference is similar to perception from a 3 dB change in signal-to-noise ratio (Templeton, Sacre, Mapp, and Saunders 1993).

Table 4-1. Speech Transmission Index (STI) scores by spectrally different noises under different noise levels, Dauer Hall 342.

Background noise (dBA)	STI scores under 4 spectrally different noises					
	Mean	N	Std. Deviation	Minimum	Maximum	Range
35	0.62	24	0.00	0.61	0.63	0.02
45	0.59	24	0.01	0.57	0.61	0.03
55	0.50	24	0.02	0.46	0.53	0.07
65	0.31	24	0.03	0.26	0.35	0.10
75	0.11	24	0.04	0.07	0.17	0.10

Dauer Hall 68 Simulation Results and Analysis

Figure 4-3 shows the STI scores in Dauer Hall 68. This room has a shorter reverberation (0.57 seconds) than Dauer Hall 342 (RT=1.21seconds) in spite of having a larger ($30m^3$) room volume because more sound absorbent materials were used in this room,. Both noise level effects ($df_1=4$, $df_2=100$, $F=4831.20$, $p<0.01$) and noise spectrum effects ($df_1=3$, $df_2=100$, $F=34.56$, $p<0.01$) are shown in Figure 4-3. The STI scores decreased by 0.67 scores from 0.73 to 0.06 over the noise level change from 35 dBA to 75 dBA. Different STI scores were measured for different types of noises under same noise-level conditions. The effects of noise spectra on STI scores changed according to noise level. At low noise levels, similar STI scores (average 0.73 with 0.05 range for 35 dBA noise condition and 0.65 STI scores with 0.08 range for 45 dBA noise condition) were measured over different noise spectra. However, significant noise spectral effects ($df_1=3$, $df_2=60$, $F=42.649$, $p<0.01$) were measured at increased noise levels (55, 65, 75 dBA).

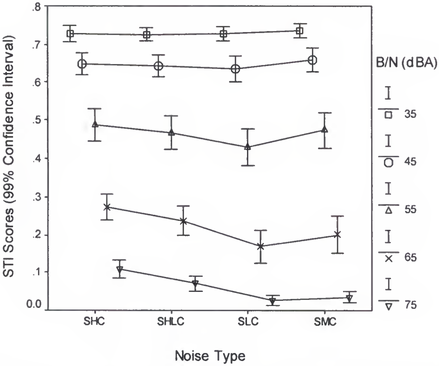


Figure 4-3. Speech Transmission Index (STI) under 4 different noise spectra and 5 different noise levels (Dauer Hall 68)

Table 4-2. Speech Transmission Index (STI) scores by spectrally different noises under different noise loudness (Dauer Hall 68)

Background noise level (dBA)	STI scores under 4 spectrally different noises					
	Mean	N	Std. Deviation	Minimum	Maximum	Range
35	0.73	24	0.01	0.71	0.75	0.05
45	0.65	24	0.02	0.61	0.69	0.08
55	0.46	24	0.03	0.39	0.52	0.13
65	0.22	24	0.05	0.14	0.29	0.15
75	0.06	24	0.03	0.02	0.12	0.11

From Table 4-2, Dauer Hall 68 shows a larger variation in STI than Dauer Hall 342 (shown in Table 4-1). The difference in STI variation between the two rooms possibly came from the variation of available source loudness at receiver locations. Because of larger room size, Dauer Hall 68 has large variations in source-receiver distance and this caused the variation in available source loudness (Table 4-3).

Table 4-3. Distance between source and receivers and source levels

		Receiver Number						Avg.	Std. Dev.
		1	2	3	4	5	6		
Distance (meter) from Source to Receiver / Source Level (dBA)	Dauer Hall 68	6.9/ 60	6.9/ 60	7.1/ 60	4.6/ 62	4.2/ 62	4.4/ 62	5.7/ 61	1.4/ 1.1
	Dauer Hall 342	5.2/ 67	4.8/ 68	5.2/ 67	3.5/ 68	2.9/ 68	3.5/ 68	4.2/ 68	1.0/ 0.5

Differences were found between Table 4-1 and Table 4-2 and the comparison is shown in Figure 4-4.

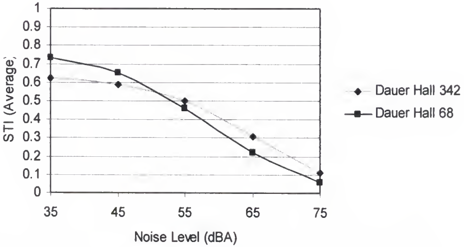


Figure 4-4. STI comparison between Dauer Hall 342 and Dauer Hall 68

Under low background noise conditions (35 and 45 dBA), Dauer Hall 68 (RT =0.57 sec) showed higher overall STI scores than Dauer Hall 342 (RT=1.21 sec). However, higher overall STI scores were measured from Dauer Hall 342 under increased noise levels (55, 65, and 75 dBA). This result is comparable with Houtgast and colleagues' (1980) study results. In their study, they showed monotonic STI increases with decreasing reverberation time in the absence of interfering noise. However, the presence of noise demanded longer reverberation time for maximum STI (e.g., RT of 0.2

sec for 40 dBA B/N, RT of 0.4 sec for 45 dBA B/N, RT of 0.5 sec for 50 dBA, and RT of 1.0 sec for 55 dBA B/N).

The increase of RT for maximum STI under noise conditions can be explained by the changes in reflected early sound energy. The reflected early sound energy can be increased under the extended reverberation time condition and the reflected early speech signals increase loudness in agreement with the law of the sound energy addition and can pleasantly modify the listener's impression of the sound (Hass 1972). Increased early reflection can compensate for noise and increase speech intelligibility (Bistafa and Bradley[1] 2000 and Hodgson and Nosal 2002). Therefore, longer reverberation time is required to maximize the speech intelligibility under increased noise level conditions.

In both studies of the computer simulation of rooms, the effects of spectrally different noises on STI scores were significant ($p<0.01$). Among spectrally different background noises, SLC (noise with strong low frequency components) showed the largest STI score drops than any other types of noise.

Field Measurement Result

Noise measurements and recordings were made in 41 classrooms in 7 schools. Five different types of air conditioning systems were found in the classrooms including: self-contained wall mounted package unit; self contained wall mounted package unit with supply duct run; roof top unit; heat pump with split system; and VAV central station air handling units and an air cooled chiller.

Six schools were using both regular classrooms and portable classrooms as an educational facility. Noise measurements and recordings were taken in portable classrooms as well as regular classrooms. A total of 135 measurements were made in this study. Eighty-two measurements were taken at student seating areas close to noise sources. Fifty-three measurements were made at noise source locations. A total 22 different types of noise sources were found in this classroom measurement study.

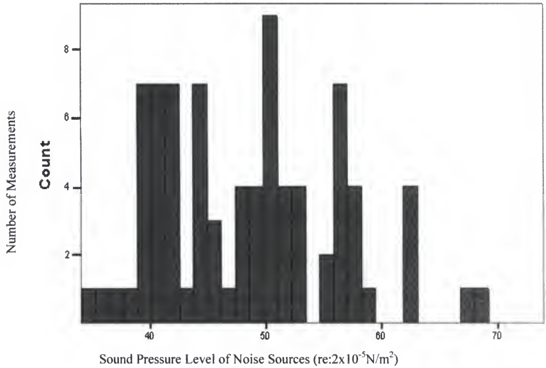


Figure 4-5. Noise levels at student seating areas

Figure 4-5 shows a histogram of the overall A-weighted noise levels from various noise sources measured in the student seating locations. Generally measured noise levels in the students' seating areas were higher than ANSI recommendations. Among 82 noise level measurements in student seating areas, only 2 measurements were lower than 35dBA, which is the recommended classroom background noise level by the new ANSI standard (Figure 4-6). In order to find spectral characteristics of noise sources before room effects and other sources, measurements were also taken at source locations. Measurements should be taken inside of an anechoic chamber or similar condition to acquire "a pure" spectrum of a noise source. However, in this study measurements were taken in the classrooms to test the actual effects of each noise source in real classrooms. Other noise sources were turned off when possible to minimize their effects on the data.

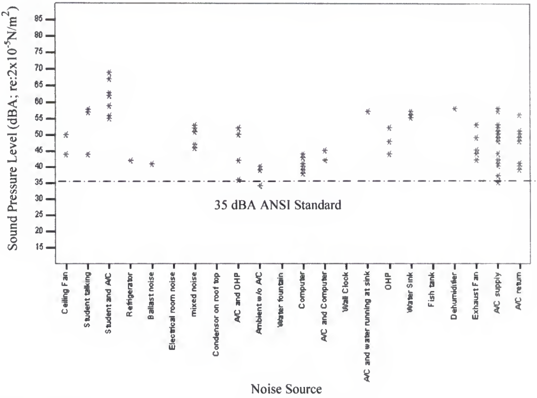


Figure 4-6. Noise sources and loudness at student seating areas

Measurements were usually taken with the sound level meter held 1m from the noise source. When surrounding noises were clearly audible, measurement distances between the source and sound meter were less than 1m. This helped in acquiring a less contaminated spectrum of the targeted noise source. A total of 53 measurements were made over 16 spectrally different noise sources. Most noise sources were over 50 dBA at the source locations as can be seen in Figure 4-8. Overall, average noise levels at both student seating areas and source locations were higher than the ANSI recommended level of 35 dBA. As can be seen from Figures 4-6 and 4-8, large variations in loudness were found among noise sources.

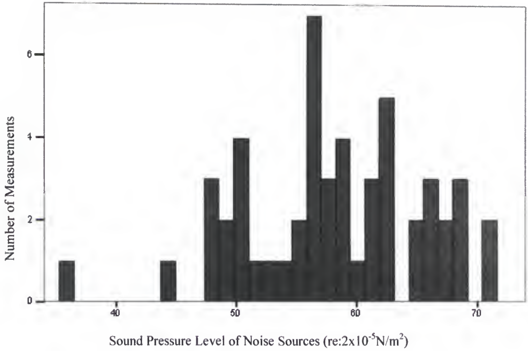


Figure 4-7. Noise levels measured at source locations

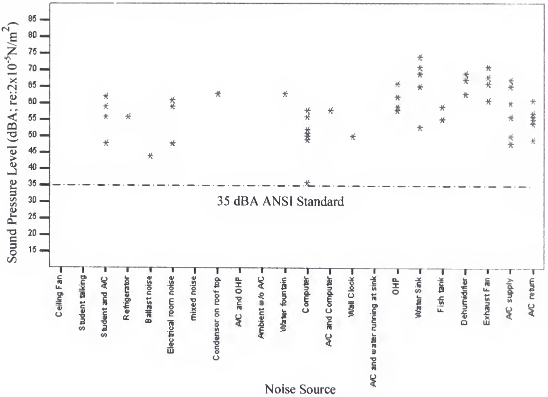


Figure 4-8. Noise sources and loudness at source locations

Measurements of HVAC system noise varied by 20 dBA in the student seating area depending on the types of A/C systems and conditions of the equipment. Running water noises measured at source locations also varied by 20 dBA depending on water faucet conditions. A noise level change of 20 dBA is heard as four times as loud by people of normal hearing. The measurement results are presented in the following series of graphs. Each figure shows the noise spectra and the noise level of various noise sources. Each line in the figure defines a different measurement. The average, possible minimum, and possible maximum noise levels and spectra were determined from the measurement data.

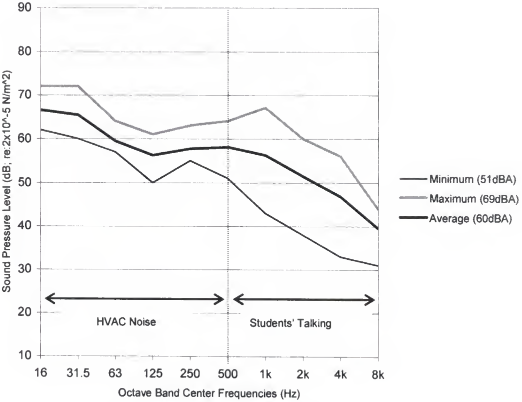


Figure 4-9. Noise levels and spectra of air-conditioning system noise and students' talk at student seating areas

Figure 4-9 shows noise spectra measured at the student seating areas. Both noise from air-conditioning systems and students' talk were included in the noise spectra. During the measurement session, the dominant noise source was students talking having an average level of 60 dBA. This level is 15dBA higher than the average noise level from the air-conditioning systems. The voice-dominant speech and air-conditioning noise showed similar spectral characteristic at mid and high frequencies with speech spectra from Pearsons and colleagues' (1977) study. Meanwhile, the shape of the noise spectra from the air-conditioning system, shown in Figures 4-16 and 4-17, shows similarity with Figure 4-8 at low frequencies. The two descriptions clearly showed that the main contributor of intense sound energy at the low frequency area was air-conditioning system noise and the main causes of high levels of sound energy at high frequencies was students' talking.

Figure 4-10 shows the noise spectra of dehumidifiers. Dehumidifiers were being used in some classrooms due to moisture problems. Dehumidifiers were measured from 63 dBA to 69 dBA at the source locations. A lower noise level of 58 dBA was measured at student seating areas. From the noise level comparison between source location and student seating areas, an average of 7 dBA of sound attenuation was found. Due to the distance between the noise source and the seating area and sound absorption by surface materials, larger noise attenuation was found at high frequencies than at low frequencies. Even after some noise attenuation, noise levels from dehumidifiers were still higher at student seating areas than the ANSI standard because of high levels of low frequency noise (57-62 dB). Without proper treatment, dehumidifiers can be a serious noise problem. Teachers stated that the dehumidifiers were not used during classes due to the high noise levels.

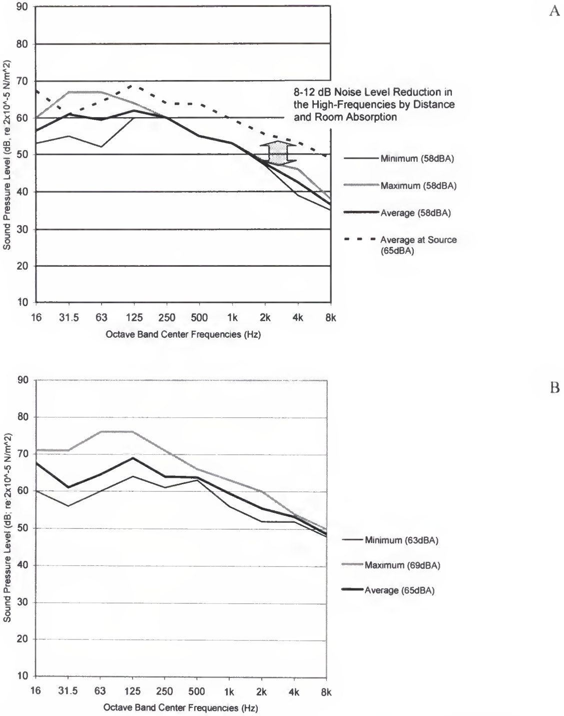


Figure 4-10. Noise levels and spectra of dehumidifiers. A) measured at student seating areas. B) measured at noise source locations.

Many classrooms were equipped with sinks. Some teachers indicated the running water noise from the sink as the most disturbing noise during class. Figure 4-11 shows the noise spectrum of both running water noise at the sink and noise from self-contained wall-mounted A/C units. The faucet was not fully opened and noise from A/C was loud during measurement. The noise spectra of water running at sinks without air-conditioning system noise can be found in Figure 4-12.

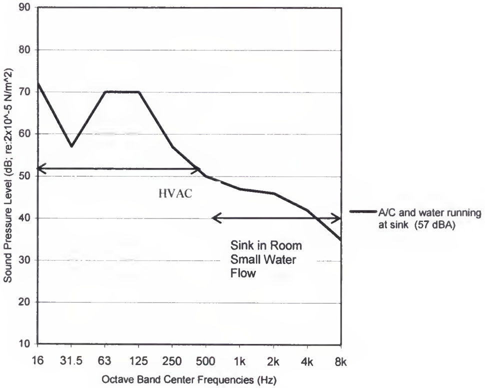


Figure 4-11. Noise spectrum of A/C and running water noise at sink measured at student seating areas.

Figure 4-12 shows different noise spectra from Figure 4-11 which included both air-conditioning system noise and running water noise at the sink. It was found that the noise spectrum of running water at the sink can differ depending on the degree of faucet opening. A high level of sound energy can be found at both low and high frequencies from the water sink noise spectra shown in Figure 4-12. This spectral characteristic was the same at both the student seating areas and noise source locations.

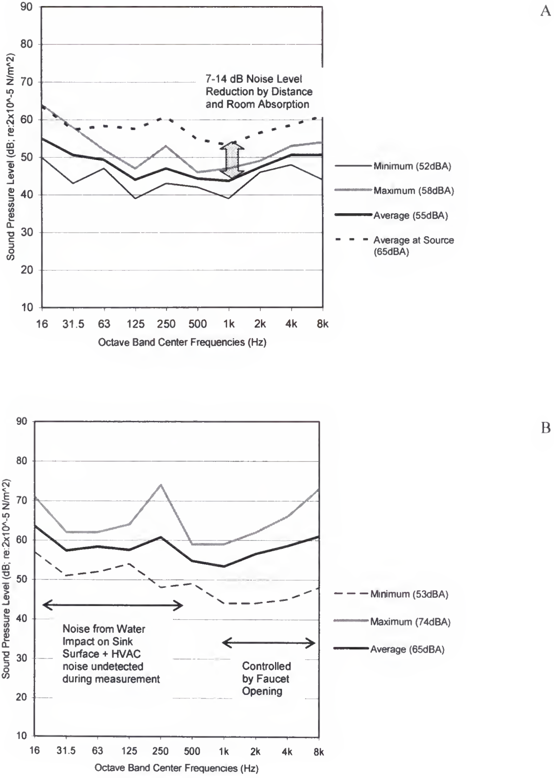


Figure 4-12 Noise spectra and levels of water running noise from Sinks. A) at Student Seating Areas. B) at Noise Source Locations.

The perceived loudness at student seating (55 dBA average) areas is approximately ½ as loud as the perceived loudness at source locations (65 dBA average) because of the 10 dBA noise level reduction.

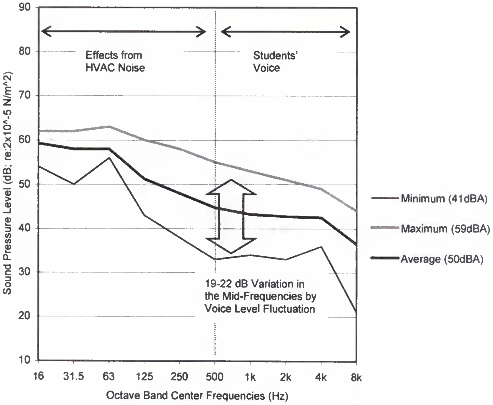


Figure 4-13 Noise spectra of students' talk

Student talking was one of the most distinctive noise sources during the measurements. Figure 4-13 shows the noise spectra of students talking. A19-22 dB variation in the mid frequencies was found in the sound levels of student voices measured. The variation was attributed to fluctuations in the loudness of student voices and the number of students talking. The noise spectrum of the average value from this measurement showed similarity with Pearsons and colleagues' (1977) study results at mid and high frequencies. Even though noises from HVAC units were not distinctive during the measurements, noise from HVAC systems was included in this measurement.

HVAC noise was the major source of sound energy at low frequencies of Figure 4-13.

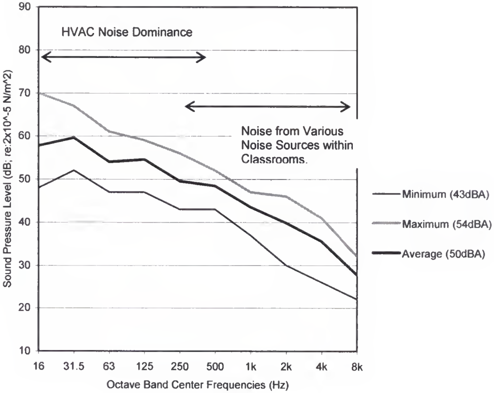


Figure 4-14. Noise spectra and noise level of mixed noises at students seating areas

Figure 4-14 shows noise spectra of mixed noise source measurements. In some cases, too many noise sources were found and it was difficult to identify the most distinctive noise source(s). Each noise source contributed to the total noise level. The average noise level of these measurements was 50 dBA. Most measurements were around 50 dBA, with a 2.82 standard deviation and normal distribution.

It is very common for teachers to use many types of multi-media equipment during a class. Overhead projectors (OHP) are one of the most common types of equipment used. Most classrooms visited were equipped with an OHP. The ANSI 12.60 standard excludes noise from people inside buildings or sound generated by temporary or permanent instructional equipment.

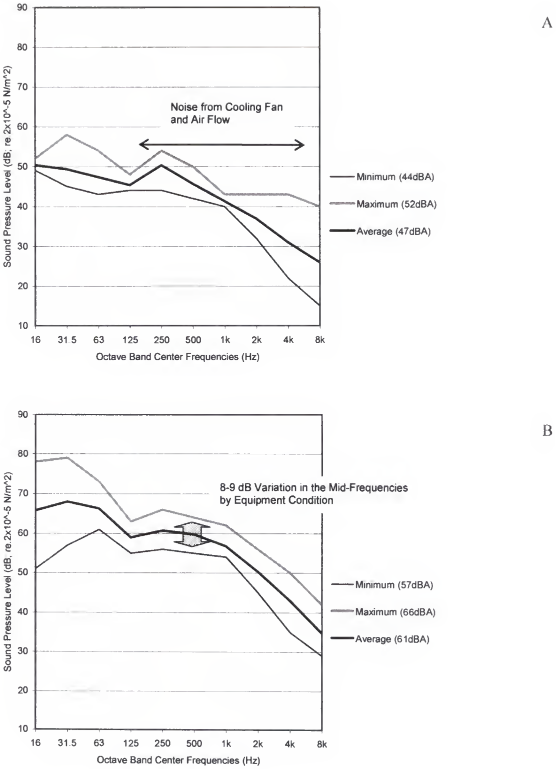


Figure 4-15. Overhead projector noise spectra and noise levels. A) measured at student seating areas. B) measured at noise source locations.

However, some instructional equipment generates 61 dBA source locations which is much higher than the 35 dBA in the ANSI standard. The main contributors to the OHP noise were cooling fans and air flow induced by the cooling fans. An 8-9 dB variation in the mid frequencies was measured in the noise levels of OHP's measured. The variation in the measurements was caused by the condition of the equipment. Average noise levels of 47 dBA were measured at the student seating areas. The loudness of OHP noise was reduced to one half as loud due to the distance from source to the seating area. In many studies, noise from HVAC systems was considered as the most significant noise source. Figures 4-16 and 4-17 show the noise spectra from each supply and return duct. Noise spectra were measured at both student seating areas and source locations. As can be seen in the figures, higher sound levels were measured in the low frequencies than the high frequencies in both supply and return cases. The shapes of the noise spectra at the student seating area and the source locations are similar because noise source spectral characteristics were maintained with little change during transmission to the student seating areas. This spectrum similarity can be clearly found from return grill noise measurements. From supply register noise measurements, the similarity can be found in the 250 Hz to 8 kHz frequency range. However, a spectral difference can be found in the 31.5 Hz to 250Hz frequency range. This difference came from a limited number of noise source measurements. Sound attenuation by distance between the source and the student seating area and room absorption resulted in 8-11 dBA differences in noise levels between the source and the receiver. Noise from air conditioning systems was categorized according to system types. Figure 4-18 shows supply register noise spectra of various systems measured at the student seating area.

Noise spectra from the return grills are shown in Figure 4-19.

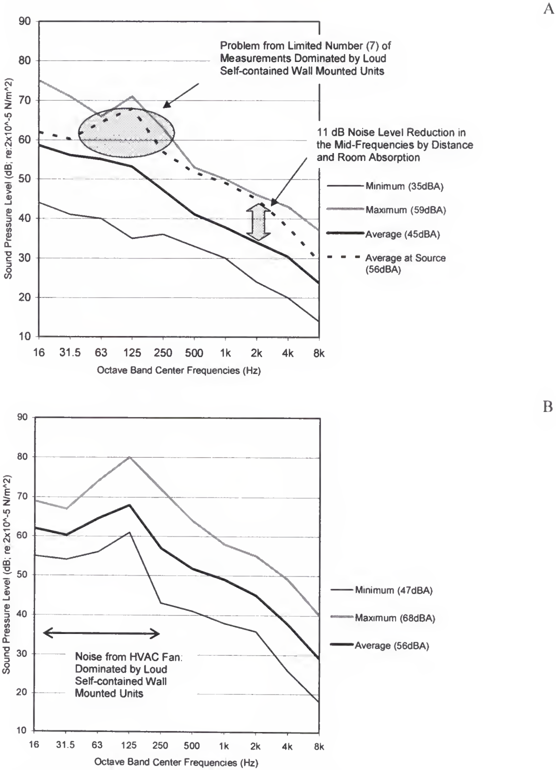
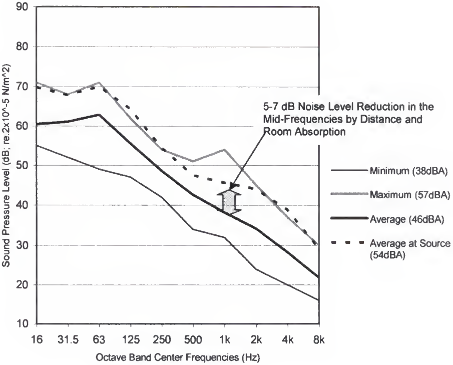


Figure 4-16. Noise spectra and levels from supply registers. A) measured at student seating areas. B) measured at noise source locations.

A



B

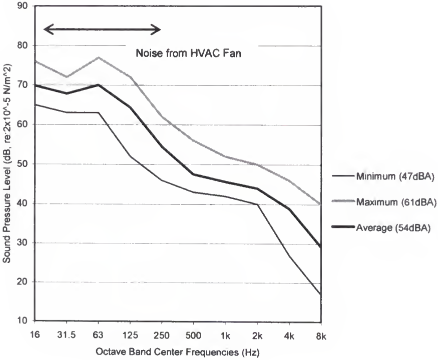


Figure 4-17. Noise spectra and levels from return grills. A) measured at student seating areas and B) measured at source locations.

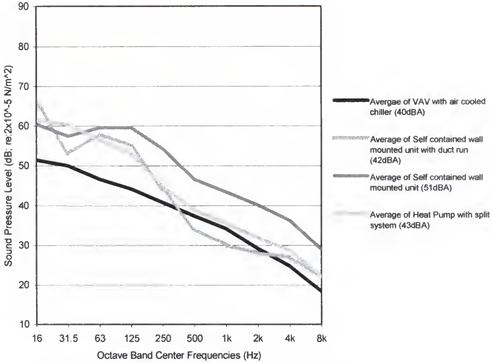


Figure 4-18. Summary of noise from supply grills at students seating areas.

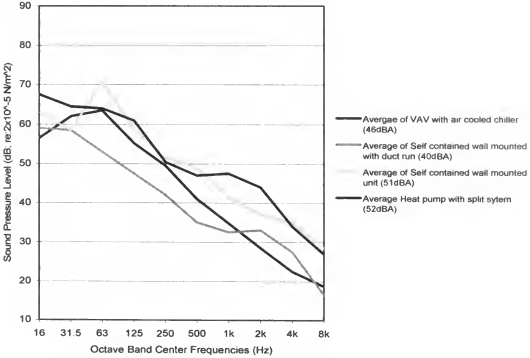


Figure 4-19. Noise spectra of return grills measured at student seating areas.

Self-contained wall mounted units and heat pumps with split systems produced high noise levels of 51 dBA and 52 dBA (this is lower than Siebein and colleagues' study (2000) result of 61 dBA) and central VAV systems produced the lowest noise level of 40 dBA (this is similar to Siebein and colleagues' study result of 43 dBA). Figure 4-18 and 4-19 show that the most typical problem of mechanical cooling systems is high noise level at low frequencies, between 16 Hz and 500 Hz. According to the ASHRAE handbook (1999) shown in Table 2-3, air turbulence and the fan are the main contributors to this noise problem.

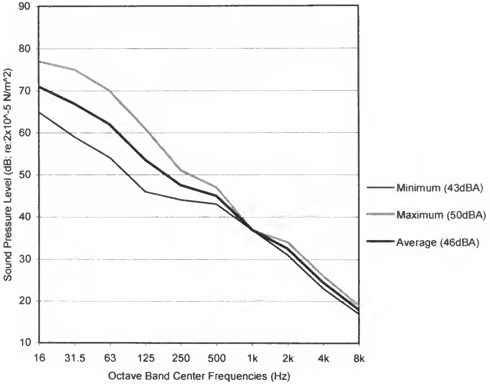


Figure 4-20. Noise spectra of ceiling fan measured at student seating areas

Ceiling fans were used as well as a self-contained wall-mounted unit as a cooling system in some of the old classroom units. However, only self-contained wall mounted units with duct runs were used as the cooling system at new building units.

Slowly circulating large-size blades generate low frequency dominant noise (Figure 4-20).

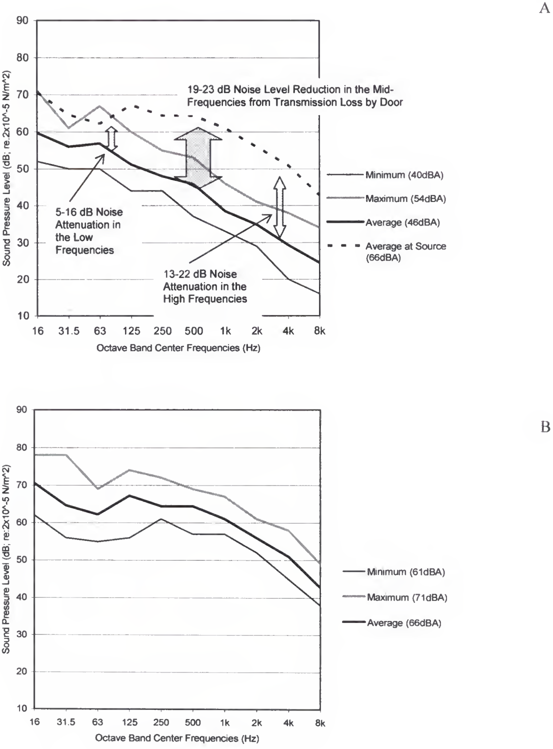


Figure 4-21. Noise spectra of restroom exhaust fans. A) measured at students' seating areas. B) measured at source locations.

Restrooms were found in most of the classrooms. Either natural or forced ventilation was used for exhaust. Exhaust fans were used for forced ventilation. Fast circulating fan blades generate intense sound energy over all frequency bands. Figure 4-21 shows exhaust fan noise spectra measured at both the student seating areas (with a closed restroom door) and at the source location. Approximately 20 dBA of noise reduction was achieved by a restroom door. Higher noise level reductions were measured at high frequencies (13-22 dB) than low frequencies (5-16 dB) because of the mass and density of door materials Even though noise from the restroom exhaust fans was high, average 46 dBA, teacher responses about the noise were not critical. This is likely because the occurrence of exhaust fan noise during class is very limited.

Computers were found in every classroom, often on a table remotely located from the student seating area. The average noise level at the computer table was 50 dBA. Approximately 40 dBA of computer noise was measured at the student seating area. The loudness of computer noise at the table where the computer was located was heard as approximately two times as loud as the computer noise heard in the student seating area. Noise from computers can be reduced by purchasing quieter computers, adding room absorption and providing distance between noise sources and the student locations. Figure 4-22 shows the computer noise measurement results at both the student seating areas and source locations. Noise from the computers was the main contributor to high and mid frequency noise. Meanwhile, noise from the HVAC system was considered as the major noise source in the low frequencies. Substantial noise reductions (7-11 dB) in the mid and high frequencies were measured at the student seating areas. Relatively small reductions were measured in the low frequencies (1-8 dB).

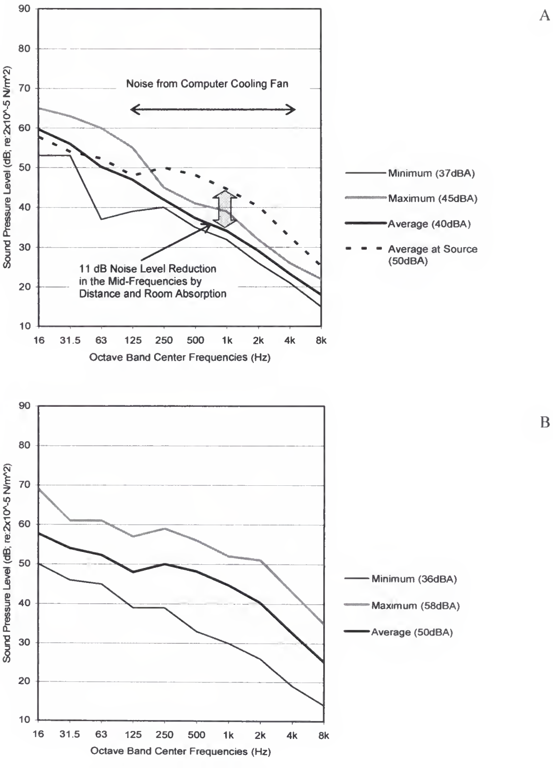
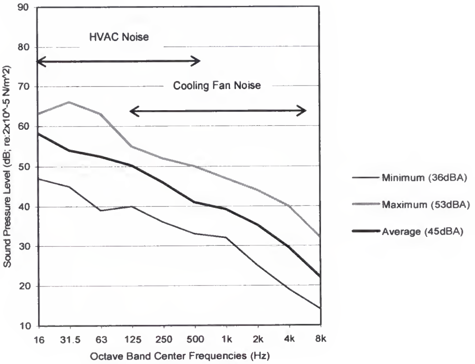


Figure 4-22. Computer noise spectra. A) measured at student seating areas. B) measured at noise source locations.



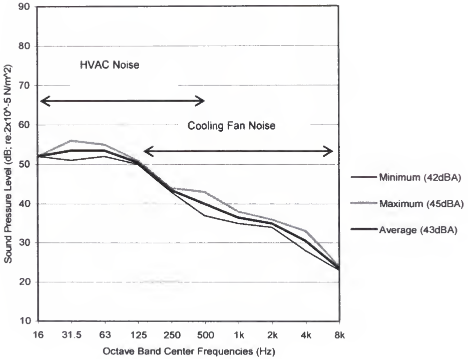


Figure 4-23. Noise spectra of combined noise sources. A) measured air-conditioning system and OHP noise at student seating areas. B) measured air-conditioning system and computer noise at student seating areas.

Figure 4-23 shows the noise spectra of combined noise sources measured at the student seating areas. When two spectrally similar noise sources were combined, the noise spectrum of the combined noise was not very different from that of each source. Only minor spectral changes were found in a relatively louder noise source. For example, when the air-conditioning system and OHP noise were combined, only small spectral changes were observed. The sound levels in the low frequencies of the combined noise were similar to the air-conditioning system noise spectrum, which has more sound energy in low frequencies. Similar results were observed in the combined air-conditioning system and computer noise case.

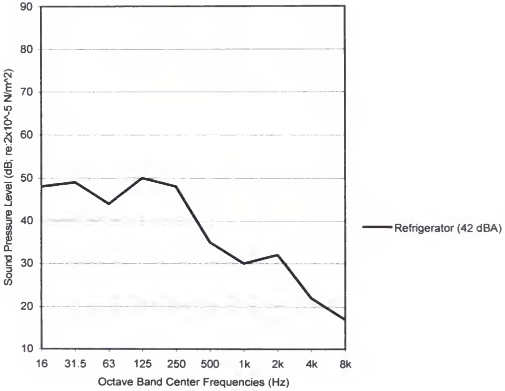


Figure 4-24. Refrigerator noise spectrum at student seating area.

Refrigerators were not very common within classrooms. Only small numbers of classrooms were equipped with a refrigerator. The noise from refrigerators was louder when the compressor was running. Even though it was relatively quiet (42 dBA) at the student locations compared to other noise sources, noise from the refrigerator was clearly audible at the student seating area under quiet room conditions. The noise was still higher than the ANSI recommendation of 35 dBA. The spectrum shows that most sound energy was located in the low frequencies (see Figure 4-24).

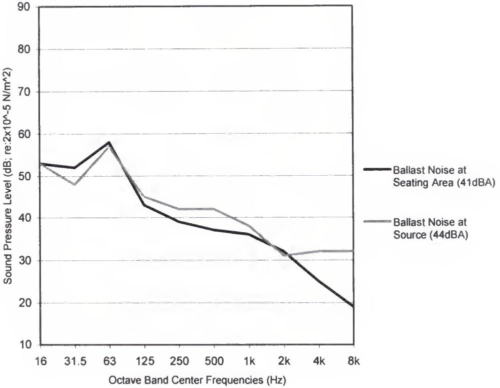


Figure 4-25. Noise from fluorescent light ballast at student seating areas.

Unlike incandescent lamps, fluorescent lamps and high intensity discharge lamps (HID) use ballasts to limit current and provide starting voltage. A magnetic lighting ballast can produce a loud 'humming' or 'buzzing' noise from internal ballast vibration. This problem can be reduced by using "high frequency electronic ballasts" instead of "magnetic ballasts." Figure 4-25 shows the spectrum from ballast noise measured near the source and in the student seating area under the fluorescent lamps. Figure 4-25 showed approximately 3 dBA of sound attenuation due to the distance between the source and students' seating area and room absorption.

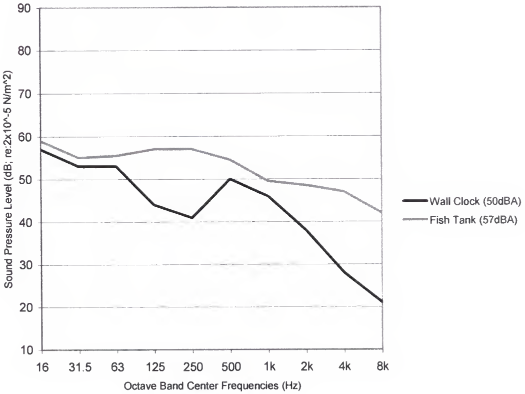


Figure 4-26. Wall clock noise and fish tank noise at source locations.

Some noise sources were clearly audible at source locations but were not measurable in the students' seating area. The distance between the source location and the student seating area was sufficient to reduce the noise level below the other ambient noises in the rooms. Noise from wall clocks and fish tanks were in this category. These noises were easily masked by other louder noise sources, or by sources located closer to the students. As can be seen from Figure 4-26, more sound energy can be found in the low and mid frequencies at the source. However, measurements at the student seating area were not possible to make due to the existence of other louder noise sources.

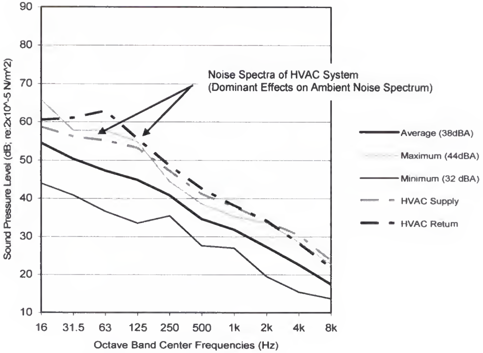


Figure 4-27. Ambient noises.

The spectra of ambient noise, without any distinctive noise sources, can be found in Figure 4-27. Even without the existence of a distinctive noise source, noise levels within classrooms were approximately 3 dBA higher on average than the ANSI recommendation of 35 dBA. Generally, noise with high levels of low frequency sounds was the most dominant noise within classrooms because of the high level of low-frequency noise energy from the HVAC systems.

A total 22 of distinctive noise sources were found in 135 classroom measurements. Among the 22 noise sources, 17 were clearly heard at the student seating areas, and 16 distinctive noise sources were measured at the source locations. The spectra and overall A-weighted noise levels of each noise source are shown in Figure 4-9 through 4-27 and Appendix B. The overall results of the study can be found in Figures 4-28 and 4-29.

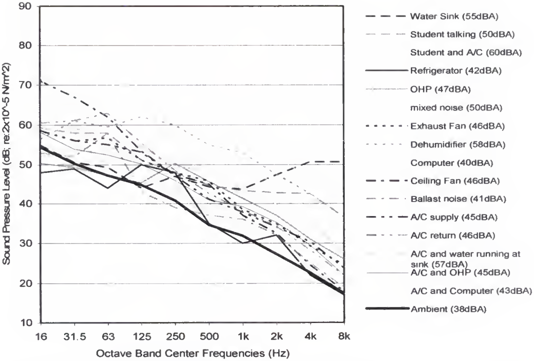


Figure 4-28. Noise spectra of various noise sources measured at student seating areas.

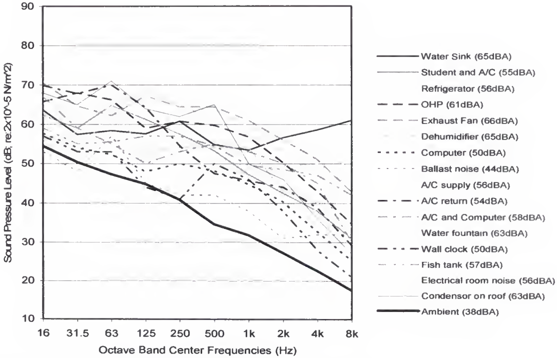


Figure 4-29. Noise spectra of various noise sources measured at source locations.

Figures 4-28 and 4-29 show noise measurement results taken at the student-seating areas and source locations, respectively. Each line represents the average of multiple measurements of specific noise sources. From visual inspection, spectral similarity can be found among most of the various noise spectra. Relatively high sound levels could be found in the lower frequencies and lower sound levels could be found at higher frequencies. Classrooms were affected by strong low frequency sound energy from HVAC systems and this affected the noise spectra of most noise sources within classrooms. However, the noise spectrum of running water at the sink showed a different spectral pattern. Almost equal sound levels could be found in the low and high frequencies. The spectral characteristic correlation test showed that running water noise was spectrally different from other noise sources with a 0.01 significance level. The spectral difference of running water noise from other noise sources could be found from measurements at the seating area and measurements at the source location. When noise spectra measured at source locations were compared, a correlation test showed that the ballast noise spectrum was different from the water fountain noise spectrum. Noise levels at the student seating areas were lower than noise levels at source locations due to attenuation factors such as distance between noise source and seating area, existence of barriers between source and receiver, and room absorption.

Figure 4-30 shows a summary of noise reduction among different noise sources measured during this study. Noise reductions ranging from 3 dBA to 19 dBA were achieved by isolating the noise sources away from the student areas. Most of the noise reductions were at high and mid frequencies due to the distances between noise sources and student seating areas.

However, only small amounts of sound level reductions were measured at low frequencies.

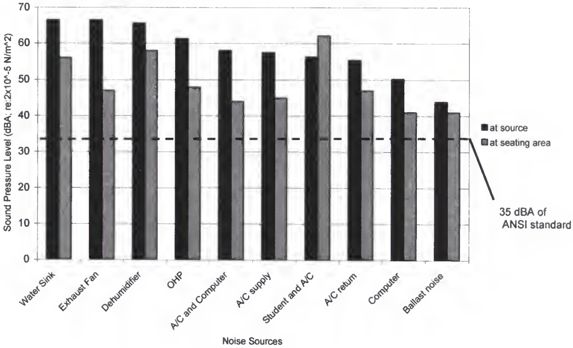


Figure 4-30. A-weighted noise levels of various noise sources

Two types of noise spectra were found in classrooms in this study. The first type of noise spectrum, which was most common in the sampled classrooms had higher sound levels in the lower frequencies compared to the middle and high frequencies (SLC). Most noise sources within classrooms were in this category. The loudness of this spectrum at the student seating area ranged from 34 dBA for one of the ambient noises to 69 dBA for the air-conditioning system and student talk. The second type of noise spectrum was the spectrum of running water at a sink. In this spectrum almost equal sound levels were found in both low and high frequencies (SHLC). The loudness of noise in this spectrum varied from 53 dBA to 74 dBA at source locations. The noise level was determined by the degree of faucet opening.

Findings from this study were used for the speech-perception test under various noise level conditions. Noise with speech spectrum has been commonly used as a background noise during speech-perception tests. However, two actual noise spectra (SLC and SHLC), found in this study, were used for the following speech-perception tests. Speech-perception tests were conducted under more realistic classroom conditions by using actual noise spectra from classrooms.

Human Subject Speech-Perception Study Result

The results of the speech-perception tests using human subjects (13 for the first test, 19 for the second test) under 16 different noise conditions (4 noise levels and 4 noise types) are summarized in Table 4-4. Both recorded noises from classrooms and spectrally-adjusted pink noise with the spectral characteristic of the recorded noise were used as background noises for this study.

Table 4-4. Speech-perception test results under different noise levels and spectra.

Noise Level (dBA)	Speech Perception (%)											
	SHLC(recorded)			SLC(recorded)			SHLC(generated)			SLC(generated)		
	Mean	Standard Deviation	Standard Error of Mean	Mean	Standard Deviation	Standard Error of Mean	Mean	Standard Deviation	Standard Error of Mean	Mean	Standard Deviation	Standard Error of Mean
45	91.08	4.66	1.29	96.62	2.75	0.76	97.23	2.52	0.70	98.46	2.60	0.72
55	86.77	4.73	1.31	92.31	4.15	1.15	96.00	3.65	1.01	91.08	6.14	1.70
65	74.15	10.53	2.92	86.77	10.76	2.98	83.38	7.97	2.21	55.75	18.92	3.35
75	54.74	12.58	2.89	9.68	14.69	3.37	44.84	19.44	4.46	0.63	1.50	0.34

Sound masking by noise causes reductions in speech-perception test scores. Masking is the process of the change of the audibility threshold in the presence of a (masking) noise (Yost 1993; Gelfand 1998). Masking of a sound source by a noise is largely dependent on its intensity and spectrum. In addition, the directions of source and noise sound and their relative times of arrival also effect masking.

Noise Level Effects on Speech Perception Scores

The effects of noise level on speech-perception test scores can be found from the current speech-perception test results shown in Table 4-4. A reduction in speech perception by an increasing the noise level (i.e., lower signal-to-noise ratio conditions) was found in the tests using the 4 different types of noises. The speech-perception reduction under increased background noise level (i.e., lower signal-to-noise ratio condition) is similar to those found in previous studies (French and Steinberg 1947; Licklider and Miller 1960; Nabelek and Pickett 1974; Finitzo-Hieber and Tillman 1978; Elliot 1979; Houtgast 1981; Bradley 1985).

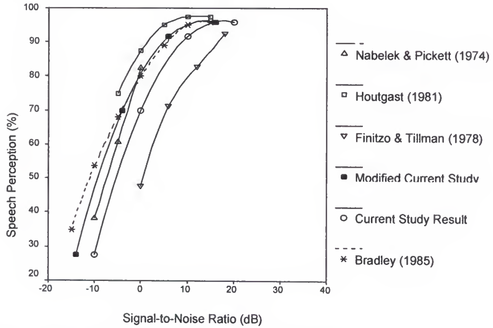


Figure 4-31. Speech perceptions under different signal-to-noise conditions.

Figure 4-31 shows the results of the current study in comparison with those of previous studies. During this study speech source and background noise levels were measured at 1m from the center loudspeaker used as the speech sound source to determine the signal-to-noise ratio. The actual speech source levels at the subjects' seating locations were an average of 4 dBA lower than the sound level measured at the 1m location because the distance between the center source loudspeaker and the subjects' seating locations was more than 1m. The sound source level attenuation by distance was considered and presented as the "modified current study curve" in Figure 4-31.

Table 4-5. Comparison of speech tests.

Study	Test Material	Noise Source	Subjects
Nabelek and Pickett (1974)	MRT	Multi-Babble Noise and Impulsive Noise	Five Females (age not specified)
Finitzo-Hielber and Tillman (1978)	50 Mono Syllabic Words	Multi-Babble Noise	12 children (age 8-12)
Houtgast (1981)	Similar to Fairbank Rhyme Test	Traffic Noise	Teachers and Students (age was not specified)
Bradley (1985)	Fairbank Rhyme Test	Not specified	9 Young adults (age 16-working age adults 8 children (age 12-13)
Current Study (S/N at Microphone Location)	MRT	Recorded classroom noises	13 adults (Average 26 year old), 19 Adults (average 22 year old)
Modified Current Study Result (Considered Actual S/N Ratio)	MRT	Recorded classroom noises	13 adults (Average 26 year old), 19 Adults (average 22 year old)

Most of the studies (except Finitzo-Hielber and Tillman's study which used young children) showed over 90% speech perception at 15 dB signal-to-noise ratio, which was recommended for good speech perception for children with hearing impairment and language disabilities (Houtgast 1981; Bradley 1986; ASHA 1995; Crandell and Smaldino, 2000). Even though different average speech-perception test scores were measured under the same signal-to-noise ratio conditions, the pattern of change in speech perception by changes in noise level was similar among different test results. The result of Bradley's study (1985) is very similar to the "modified current study" result. The variations in the results among the studies discussed above are caused by the differences in the test method in which the studies were conducted. These include differences in test material, noise sources, and test subjects as shown in Table 4-5.

Noise Type Effects on Speech Perception Scores

The results of the current study were plotted in Figure 4-32. In addition to the noise level effects ($df_1=3$, $df_2=235$, $F=518.47$, $p<0.01$) on speech perception, noise type effects ($df_1=3$, $df_2=235$, $F=33.3$, $p<0.01$) on speech perception were found. Different speech perceptions were measured under different types of noise with the same overall A-weighted sound level.

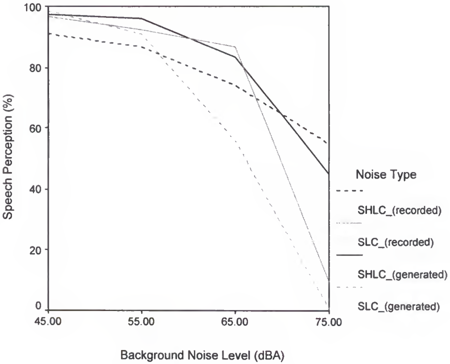


Figure 4-32. Speech perception under different noise levels and noise types

The effect of noise type on speech perception varied according to the noise level. When the noise level was 45 dBA, similar speech-perception scores (average 97.44%

speech perception) were measured under 3 different types of noise conditions: SLC (recorded); SHLC (generated); and SLC (generated), whereas lower speech-perception scores, with an average of 91.08%, were measured at the 45 dBA noise level when the SHLC (recorded) was used as the background noise. At this noise level, speech perception was affected by noise types ($df_1=3$, $df_2=48$, $F=13.10$, $p<0.01$). The Dunnett C multiple comparison test showed that speech-perception scores under SHLC (recorded) background noise was significantly different from other noise source conditions at the 0.05 level.

When the noise level was 55 dBA, the speech perception scores were affected by noise types ($df_1=3$, $df_2=48$, $F=8.31$, $p<0.01$). Lower speech-perception scores under the SHLC (recorded) background noise than other types of noises maintained similar results until the noise level reached 55 dBA. The Dunnett C multiple comparison test showed that the average speech-perception test scores of the SHLC (recorded) background noise was significantly different from SLC (recorded) and SHLC (generated) background noise at the 0.05 level.

The noise type effect ($df_1=3$, $df_2=67$, $F=19.46$, $p<0.01$) was also found when the noise level reached 65dBA. The largest decrease in speech-perception test scores occurred in the SLC (generated) noise. An average speech-perception test score of 56% was measured at this level. When the generated SLC was used as a background noise, the average speech-perception test score decreased by 43% as the noise level increased from 45 to 65 dBA. The Dunnett C multiple comparison test showed that speech-perception test scores under the SLC (generated) noise condition at this level were significantly different from speech perception under other noise conditions: SLC (recorded) , SHLC (recorded), and SHLC (generated) (p<0.05).

The noise type effect (df_1=3, df_2=72, F=69.94, p<0.01) was still found when the background noise level was increased to 75 dBA. Subjects had significant difficulties in recognizing the source sound at this noise level. Many of the test subjects' judgments were made on guesses especially when SLC (generated) and SLC (recorded) noise sources were used as the background noise. The test results clearly showed the spectral effects on speech perception at this noise level. When the background noises had strong high and low frequency components (SHLC), the average speech-perception test score was 49.79% (standard deviation=16.9). Significantly (p<0.05) lower speech-perception test scores (average speech perception=5.16 %, standard deviation=11.27) than SHLC cases were measured when background noises had a strong low frequency component (SLC).

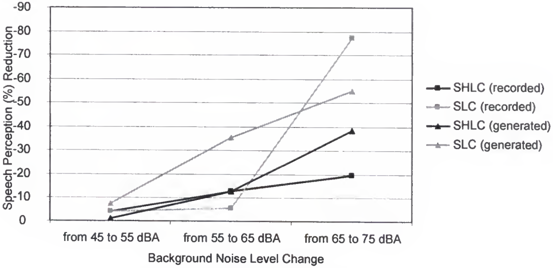


Figure 4-33. Speech-perception reduction by different types of background noise during noise level changes.

As shown from the relationship between speech-perception scores and noise level (Figure 4-31 and Figure 4-32), the speech-perception scores did not linearly decrease with an increase in the noise level. The amount of reduction in speech-perception score varied according to the noise levels and the character of applied noises. From Figure 4-33 increased reductions in speech perception can be found when the background noise changes were made at high noise level conditions.

Reductions in speech-perception scores were 31% greater when the noise level changed from 65 dBA to 75 dBA than when noise level changed from 55 dBA to 65 dBA. Similarly, the reductions in speech-perception scores were 12% greater when noise levels changed from 55 dBA to 65 dBA than when noise levels changed from 45 dBA to 55 dBA. Significant interactions ($df_1=9$, $df_2=235$, $F=27.89$, $p<0.01$) between noise level and noise type caused these variations. Part of the interaction can be explained by the upward spread of masking (changes of the masking pattern depending on the intensity and frequency of the masker). With an increase in noise level, (above 40 dBA), the greatest masking occurs at tones higher than masker frequencies over wider frequency ranges (Knudsen 1932; Ehmer 1959). Therefore, the reduction in speech perception during the noise level change from 65 dBA to 75 dBA is greater than the change in speech perception from 55 to 65 dBA due to the interaction between noise level and changed masker frequencies from upward masking. Similarly, a greater decrease in speech perception can be found when the noise level changed from 55 to 65 dBA than when the noise level changed from 45 to 55 dBA.

Noise level ($df_1=3$, $df_2=235$, $F=518.47$, $p<0.01$), noise type ($df_1=3$, $df_2=235$, $F=33.33$, $p<0.01$), and their interaction ($df_1=9$, $df_2=235$, $F=27.89$, $p<0.01$) showed significant effects on speech perception. About 89% of variances in speech perception scores can be explained by 2 main factors: the noise level and the type of noise as well as their interactions.

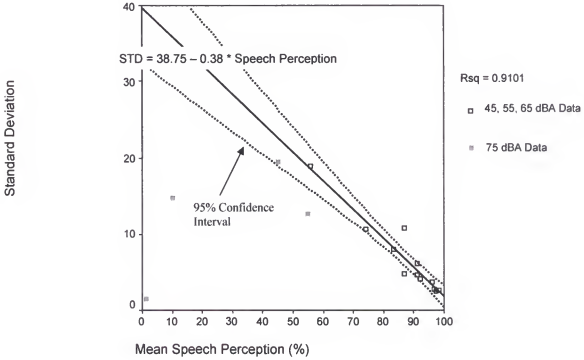


Figure 4-34. Speech perception and standard deviation (under 45, 55, and 65 dBA noise level condition).

Figure 4-34 shows the relationship between measured speech-perception scores and the corresponding standard deviations of the speech-perception test scores. For this analysis, speech-perception scores measured under 75 dBA noise conditions were not included. Because the majority of subjects responded that they could not hear the source sound during the tests due to the high noise levels. Under that condition, many responses were made from random "guesses." Speech perceptions under 45, 55, 65 dBA noise conditions were analyzed. Standard deviations of around 3 were observed at high speech-perception score conditions and deviations of over 10 were measured at low speech-perception score conditions (Table 4-4). This result is similar to the result of the computer simulation study (Table 4-1; 4-2). From this study, the relationship between speech perceptions and the corresponding standard deviations can be explained by a linear relationship: STD=39.75-0.38*Speech Perception (adjusted R^2=0.91). The large standard deviation of speech-perception test scores under high noise conditions can be also found in Bradely's (1985) study. The large deviation under high noise levels can be explained by the limited or distorted source information heard in the presence of the loud background noise. Under this condition, listeners used limited acoustic information to make judgments, and this resulted in large standard deviations in speech-perception test results.

In addition to loudness, other factors, such as the spectral and temporal characteristics of noise, as well as content, decide the overall noise characteristics. Speech perception can be affected by these factors (Levitt and Webster 1991). So far, analyses were made on the effect of noise level and noise type. Noise types used in the analyses include other factors. The following analyses shown in the following pages were made over the effects of the factors that determine noise type. As mentioned before, because of the loudness of 75 dBA background noise and its effect on speech perception, analyses were made with and without speech perception under 75 dBA noise conditions.

Table 4-6. Analysis of variance for spectral and content effects on speech perception.

Noise Level and Spectral Effect	P-value	Noise Level and Content Effect	P-value	
	SLC generated vs. SHLC generated		SLC recorded vs. SLC generated	SHLC recorded vs. SHLC generated
Noise Level	0 / 0	Noise Level	0 / 0	0 / 0
Noise Spectrum	0 / 0	Noise Content	0 / 0	0 / 0.07

(45,55,and 65 dBA noise condition / 45,55,65, and 75 dBA noise condition)

Noise Spectral Effects on Speech Perception Test Scores

Tests were performed to check the noise spectra and content effects on speech perception as shown in Table 4-6. Speech perceptions under $SLC_{generated}$ and $SHLC_{generated}$ noise conditions were measured. From this comparison, the noise spectral effect on speech perception was measured without the effects of other factors. From the overall analysis, a significant noise spectral effect on speech perception was found ($df_1=1$, $df_2=91$, $F=16.99$, $p<0.01$/ $df_1=1$, $df_2=127$, $F=71.39$, $p<0.01$).

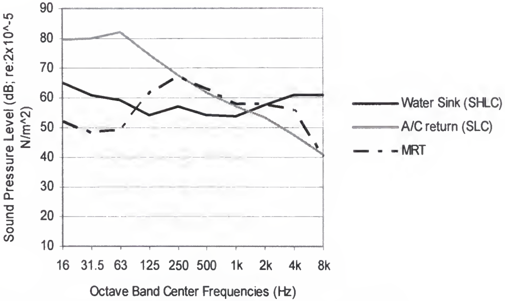


Figure 4-35. Spectra of noise sources and sound sources at 65 dBA.

The effects of spectrally similar noise and sound sources on speech-perception test scores are known. When the spectra of a noise source are similar to the long-term spectral characteristics of speech (the most frequent interfering noise (Heusden et al. 1979)) noise is the most effective masker (Moore 1977; Gelfand 1998; Crandell 2000). In this study, both SLC and SHLC were not spectrally similar with the sound source, MRT material (with 0.01 significance level) as shown in Figure 4-35. Therefore, there was no direct effect from spectral similarity between the noise source and the sound source.

Miller's (1947) study showed different masking effects of spectrally different masking noises. According to his study, a wide-band masking noise was the most effective in masking speech. When narrow band noise was used, higher frequency noises masked more than low frequency noises at low noise level condition (S/N>0 dB). However, low frequency noises masked more than high frequency ones at high noise level condition (S/N<0 dB). When the signal-to-noise ratio was less than 20 dB, there was a noise spectral effect on speech perception. The overall noise spectral characteristics showed a significant effect on speech perception in this study ($df_1=1$, $df_2=91$, $F=16.99$, $p<0.01$/ $df_1=1$, $df_2=127$, $F=71.39$, $p<0.01$). However, when noise levels were 45 dBA and 55 dBA, noise spectral effects were not significant ($df_1=1$, $df_2=48$, $F=2.76$, $p=0.1$). Significant noise spectral effects ($df_1=1$, $df_2=79$, $F=102.12$, $p<0.01$) were measured at noise levels of 65 dBA and 75 dBA. Under these noise levels, greater reductions in speech-perception test scores were measured in SLC noise conditions.

Noise Content Effects on Speech Perception Test Scores

The effect of noise content on speech perception was also tested and the results can be found in Table 4-6. The effect of noise content on speech perception was also shown in Elliot et al. and Carhart's studies. Their masking comparison studies showed the effects of noise content on speech perception between multi-babble noise and equally intense electronically-generated noise having a similar spectrum (Carhart 1969; Elliot et al. 1979).

The recorded classroom noises (captured from classrooms) have specific acoustic content (information). However, electronically-generated noises have spectra similar to the recorded noises without the specific noise content. The effect of noise content was tested by comparing speech-perception test scores with both types of noise sources.

Significant noise content effects on speech perception were found ($df_1=1$, $df_2=72$, $F=33.05$, $p<0.01$) in the SHLC noise cases when noise levels were less than 75 dBA. Recorded noise, which has noise content, showed approximately an 8 % decreased speech-perception test scores than generated noise which does not have noise content. When the noise level was 75 dBA, because of the strong influence of loudness, the noise content effect could not be measured ($df_1=1$, $df_2=36$, $F=3.47$, $p=0.07$). No significant difference between recorded and generated noise was measured. When the noise levels were 75 dBA, speech-perception test scores measured under generated SHLC noise condition were approximately 10% lower than speech-perception test score measured in the recorded SHLC noise condition. This result is different from the result of the tests using lower noise level conditions because of the limited sound source information due to loud background noise. Under this condition, test subjects sometimes made random "guesses" to compensate for the lack of source information, which led to large variations in their responses (Table 4-4).

Overall, SLC noises showed significant noise content effects on speech perception ($df_1=1$, $df_2=91$, $F=15.18$, $p<0.01$/ $df_1=1$, $df_2=127$, $F=22.00$, $p<0.01$). Specifically, when noise levels were 45 and 55 dBA, there were no significant noise content effects ($df_1=1$, $df_2=48$, $F=0.07$, $p=0.79$). Both recorded and generated noises showed similar reductions in speech-perception test scores. When noise levels were over 55 dBA, generated noise caused 9-30% decreases in speech-perception test scores compared with recorded noises. The pattern found in SHLC was not found under SLC noise conditions (Figure 4-32). No constant difference between recorded and generated noise was found and a large drop in speech perception (a 31% perception test score decrease) was found in the 65dBA generated noise condition.

Noise Induced Annoyance Effects on Speech Perception Test Scores

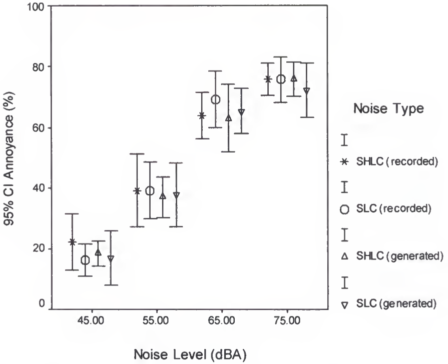


Figure 4-36. Annoyance under 16 different noise condition.

Noise induced annoyance may affect speech perception. To verify this, this factor was tested. Degrees of annoyance under 16 different background noises (4 noise levels and 4 different types of noises) were measured and factors causing annoyance were studied. A variety of components related to noise can cause annoyance. The loudness of a noise is the dominant factor in annoyance (Fidell and Green 1998). Spectral characteristics of noise are also a factor contributing to annoyance. According to Kryter (1970), noise with higher frequency components is generally more annoying than noise with lower frequency components at the same noise level.

The effect of noise level ($df_1=3$, $df_2=235$, $F=162.69$, $p<0.01$) on annoyance was significant as shown in Figure 4-36. However, different types of noises do not show significant effects on annoyance ($df_1=3$, $df_2=235$, $F=0.32$, $p=0.813$).

Table 4-7. Analysis of variance for spectral and content effects on annoyance.

Noise Level and Spectral Effect	P-value	Noise Level and Content Effect	P-value	
	SLC generated vs. SHLC generated		SLC recorded vs. SLC generated	SHLC recorded vs. SHLC generated
Noise Level	0 / 0	Noise Level	0 / 0	0 / 0
Noise Spectrum	0.89 / 0.85	Noise Content	0.67 / 0.50	0.49 / 0.51

(45,55,and 65 dBA noise condition / 45,55,65, and 75 dBA noise condition)

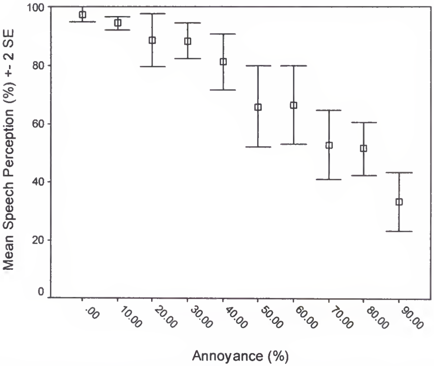


Figure 4-37. Overall relationship between annoyance and speech perception.

Table 4-7 shows the noise spectral effect and noise content effect on annoyance. According to the analyses, there were no significant noise spectral effects on annoyance ($df_1=1$, $df_2=91$, $F=0.02$, $p=0.89$ / $df_1=1$, $df_2=127$, $F=0.04$, $p=0.85$). In addition, insignificant noise content effects on annoyance were found from SLC noise condition results ($df_1=1$, $df_2=91$, $F=0.18$, $p=0.67$ / $df_1=1$, $df_2=127$, $F=0.46$, $p=0.50$) and SHLC noise condition results ($df_1=1$, $df_2=72$, $F=0.48$, $p=0.49$ / $df_1=1$, $df_2=108$, $F=0.45$, $p=0.51$). The main factor affecting annoyance was the loudness of a noise.

Figure 4-37 shows the relationship between annoyance and corresponding speech perception. Very few people reported being annoyed by noise in the relatively quiet conditions that resulted in high speech-perception scores. The percentage of subjects reporting annoyance increased as noise levels increased and speech-perception scores decreased. The effect of annoyance on speech perception was statistically significant ($df_1=9$, $df_2=241$, $F=14.32$, $p<0.01$).

CHAPTER 5
CONCLUSIONS

The quantitative effect of the type, spectra, content, and annoyance of actual classroom noises on speech perception was found in this study.

1. Previously speech perception was explained by signal-to-noise ratio and reverberation time in rooms. This study showed not only the significant effect of noise level ($p<0.01$) on speech perception but also significant effects ($p<0.01$) of noise spectrum, noise content, and annoyance of actual classroom noise.

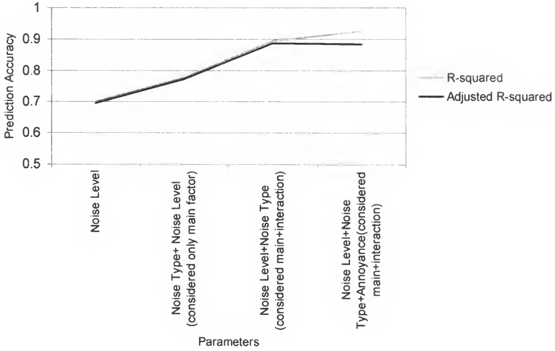


Figure 5-1. Speech-perception prediction model accuracy by noise factors.

Figure 5-1 shows the effects of noise level, noise type, and annoyance on speech perception. As can be seen from the figure, noise level can explain 70% of the variance in speech-perception test scores. When the type, which includes spectra and the content of noise, as well as the annoyance caused by the noise were added to the model, up to 90% of the variance in speech-perception scores was explained. Within classrooms, there are many different noise sources and these have different spectral characteristics and sound qualities. Therefore, not only noise levels but other noise-related factors should also be considered and controlled to allow student to reach higher percentage scores on speech perception within classrooms.

2. Noise sources with strong low frequency components (SLC) showed greater reduction in speech-perception test scores compared to noise with strong high and low frequency components (SHLC). At low noise level conditions (45 dBA and 55 dBA), similar speech-perception scores (1~5% difference in speech perception) were measured. However, as the noise level increased to 65 dBA and 75 dBA, greater noise spectra effects on speech-perception scores were measured with a 28~44% difference. This result implies that noise spectral characteristics should be considered in the assessment of speech perception in classrooms. Noise spectral characteristics should be considered for accurate speech-perception measurement especially when the noise level is over 65 dBA. According to the ANSI S12.60 standard, background noise should not exceed 35 dBA and C-weighted background noise should not exceed A-weighted background noise by 20 dB within classrooms. Adherence to the requirements of this standard will reduce deteriorating noise spectral effects on speech perception. Therefore, the application of this standard will maximize speech-perception scores within classrooms.

3. The noise profiling study identified various individual noise sources within classrooms. Those individual noise sources contributed to the overall background noise levels and

characteristics of background noise. The overall noise level found in this study was higher (an average noise level of 47 dBA) than the ANSI S12.60 recommendation (35 dBA) as shown from the "field measurement result" in Chapter 4. Two different types of noises, noise with strong low frequency components (SLC) and noise with strong high and low frequency components (SHLC), were identified from the noise profiling study. Most noise measurements were affected by low frequency components from the HVAC system. This made SLC noise type the most dominant noise type found in classrooms. Noise levels from HVAC systems as high as 59 dBA were measured in student seating areas. Noise spectral effects on speech perception are relatively small at this noise level. However, as shown in Figure 4-15, in classrooms the noise level of HVAC systems can reach as high as 68 dBA near source locations. Noise spectral effects are significant at this noise level. Students' speech perception score will be approximately 45% due to both loudness and noise spectral characteristics under this HVAC system condition, without sufficient distance between the noise source and the students. Therefore, a HVAC system should be carefully designed to keep noise levels at the 35 dBA recommended by ANSI to maximize students' speech perception. When loud HVAC systems are used, the equipment should be situated at a remote location from the students' seating area.

4. The effect of noise content on speech perception was tested. Significant noise content effects ($p<0.01$) were found, when background noises have SHLC spectral characteristic and were not extremely loud noises (<75 dBA). When SHLC was used as the noise source, the effects of noise content were similar at 45 dBA, 55 dBA, and 65 dBA levels (Figure 4-31). However, when noise levels were extremely high, the noise content effect on speech perception was not measured. Noise content effects on speech

perception were also found when background noises have SLC spectral characteristics. However the pattern found from SHLC was not found (Figure 4-31). No constant difference between recorded, and generated noise was found and a greater decrease in speech perception (about 30%) was measured at the 65 dBA generated noise condition than at other conditions. This result shows that use of an actual noise source, such as multi-babble and recorded noise sources, can provide a better indicator of actual speech-perception scores than the use of electronically generated noise. Therefore, in order to measure actual speech perception within classrooms, using a real noise source is recommended.

5. To explain speech-perception changes under different noise conditions, noise induced annoyance was analyzed. Annoyance showed a significant effect on speech perception ($p<0.01$). As shown in Table 4-7 and Figure 4-35, noise loudness was the dominant factor in determining annoyance. Because of dominant effects of the noise level on speech perception, spectral characteristic or noise content were not significant factors ($p>0.01$) in determining annoyance. Therefore, if noise level within classrooms is controlled, speech-perception score reduction from noise-induced annoyance is not expected.

6. Figure 5-2 shows the changes in speech-perception test scores according to the type of noise source. This figure was developed from the relationship between the signal-to-noise ratio and speech perception (Figure 4-30) and measured noise levels of different noise sources.

As can be seen in Figure 5-2, speech-perception scores would reach over 90% under most noise conditions found in the actual classrooms for normal hearing young-adult listeners. However, as shown in Figure 4-8, when students' activities are not controlled, the noise level within classrooms can reach up to 69 dBA. This noise level would have a significant result in speech-perception scores for the same listening group. Therefore, students' activities should be carefully controlled during classes so higher speech-perception scores can be achieved. In addition, quiet instructional equipment should be used and located at remote or isolated locations from the students' seating area to reduce background noise levels within classrooms.

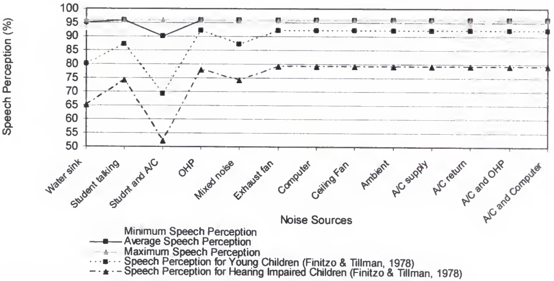


Figure 5-2. Speech perception under different noise source conditions.

Future Studies

The present study has shown the effects of different types of classroom noise on speech perception. For this study a limited acoustic environment (a room with an average reverberation time of 0.57 sec in mid-frequencies (500Hz, 1000Hz, and 2000Hz)) was used. As shown in Finitzo-Hieber and Tillman's study (1978), room reverberation interacts with the loudness of noise. The interaction of room reverberation with other factors mentioned in this study may also occur. A future study will be made using various room reverberation conditions and the specific noise sources identified in this study. The result of this future study should generalize the effects of noise factors on speech perception.

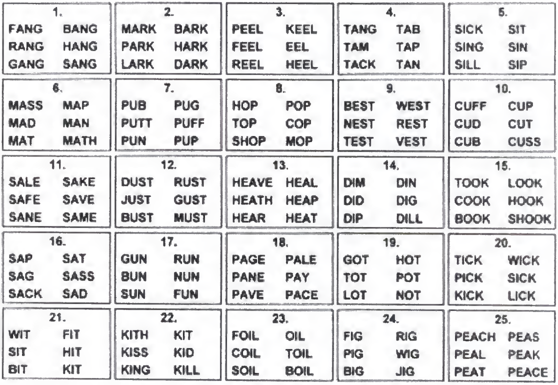
Due to the strong effects of HVAC system noise on most of the data, only 2 noise spectra were identified in the statistical analysis of the noise sources in the noise profiling study. The effects of those noise spectra were tested. The effects of other noise spectra may show different results from this study. Noise spectra measurement without HVAC noise should be undertaken and effects of other possible noise spectra will be tested in the future study.

The current study, as well as those I cited earlier in the literature review, were performed under reverberant sound field conditions. Under reverberant sound field conditions, noise levels are relatively similar over the entire seating area. However this does not reflect actual conditions in classrooms. Depending on the locations of the noise source and the distance between the noise source and seating location, students may experience different noise levels. Future studies should use actual data at each test location within classrooms. Noise level changes from noise source location should be measured and patterns of noise level changes would be found.

Studies regarding the effects of students' hearing conditions on speech perception are also necessary for further research. The current study was done under equal binaural hearing conditions. However, depending on the seating location and arrangement of the student seating area relative to the source and noise source location, some students may experience unequal binaural hearing conditions. In other words, one ear may hear noise, and the other ear may hear the source sound. These different hearing conditions may cause different speech perceptions under same source and noise level conditions. The hearing conditions at the students' seats should be measured and effects of different hearing conditions should be studied in a future study.

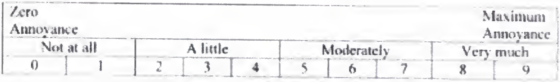
This study was done using normal-hearing young adult listeners. However, different populations such as people with hearing impairments, children, or people for whom English is a second language (ESL) may show different results than found in this study. Figure 5-2 shows the predicted speech-perception scores using Finitzo & Tillman's 1978 study results for young children and hearing-impaired children under measured classroom noise conditions. Average reductions of 7% in speech-perception scores can be expected from the young children group. More severe speech-perception score reductions averaging a 20% decrease in speech-perception scores can be expected for the hearing impaired young children group. Therefore, future studies should be conducted for different populations who are more susceptible to noise than the normal hearing adult group.

SPEECH-PERCEPTION TEST MATERIAL



1.		2.		3.		4.		5.	
FANG	BANG	MARK	BARK	PEEL	KEEL	TANG	TAB	SICK	SIT
RANG	HANG	PARK	HARK	FEEL	EEL	TAM	TAP	SING	SIN
GANG	SANG	LARK	DARK	REEL	HEEL	TACK	TAN	SILL	SIP
6.		7.		8.		9.		10.	
MASS	MAP	PUB	PUG	HOP	POP	BEST	WEST	CUFF	CUP
MAD	MAN	PUTT	PUFF	TOP	COP	NEST	REST	CUD	CUT
MAT	MATH	PUN	PUP	SHOP	MOP	TEST	VEST	CUB	CUSS
11.		12.		13.		14.		15.	
SALE	SAKE	DUST	RUST	HEAVE	HEAL	DIM	DIN	TOOK	LOOK
SAFE	SAVE	JUST	GUST	HEATH	HEAP	DID	DIG	COOK	HOOK
SANE	SAME	BUST	MUST	HEAR	HEAT	DIP	DILL	BOOK	SHOOK
16.		17.		18.		19.		20.	
SAP	SAT	GUN	RUN	PAGE	PALE	GOT	HOT	TICK	WICK
SAG	SASS	BUN	NUN	PANE	PAY	TOT	POT	PICK	SICK
SACK	SAD	SUN	FUN	PAVE	PACE	LOT	NOT	KICK	LICK
21.		22.		23.		24.		25.	
WIT	FIT	KITH	KIT	FOIL	OIL	FIG	RIG	PEACH	PEAS
SIT	HIT	KISS	KID	COIL	TOIL	PIG	WIG	PEAL	PEAK
BIT	KIT	KING	KILL	SOIL	BOIL	BIG	JIG	PEAT	PEACE

Figure A-1. Modified Rhyme Test (MRT) form



Zero Annoyance									Maximum Annoyance
Not at all		A little			Moderately			Very much	
0	1	2	3	4	5	6	7	8	9

Aspect, that especially makes you dissatisfied during the test : None / Loudness of noise / Noise color / others ( )

Figure A-2. Annoyance survey form

APPENDIX B
CLASSROOM NOISE SOURCES AND SPECTRA

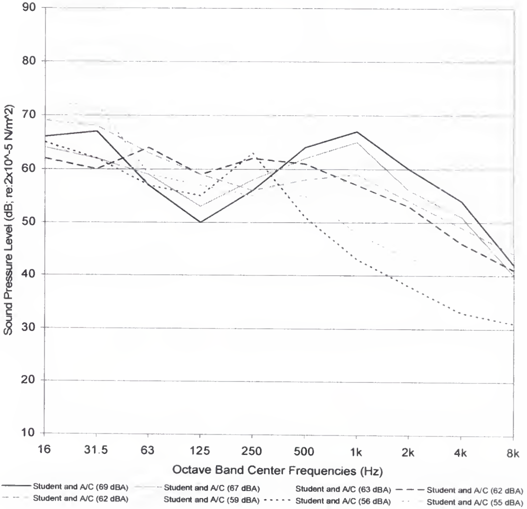


Figure B-1. Noise levels and spectra of air-conditioning system noise and students' talking at student seating areas

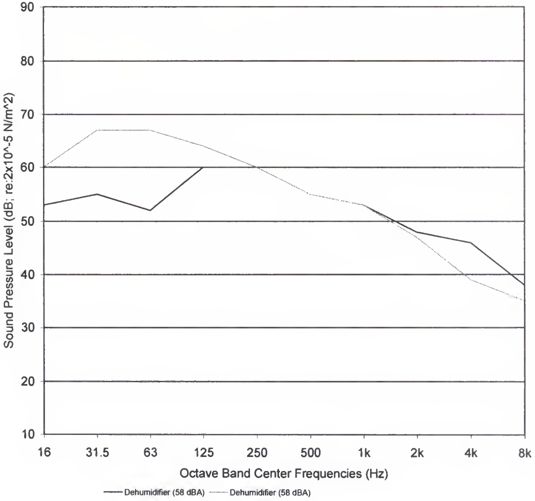


Figure B-2. Noise levels and spectra of dehumidifiers measured at student seating areas

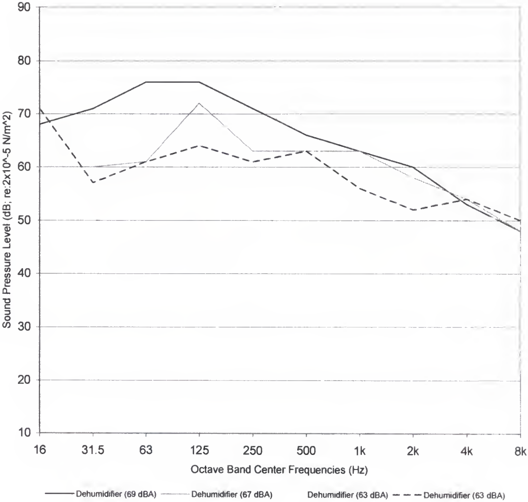


Figure B-3. Noise levels and spectra of dehumidifiers measured at noise source locations

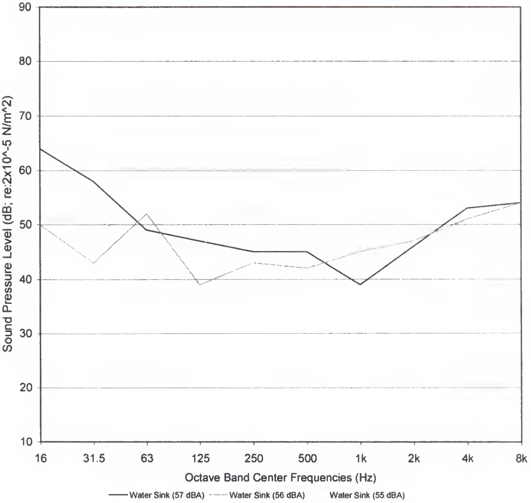


Figure B-4. Noise spectra and levels of water running noise from sinks measured at Students' seating areas

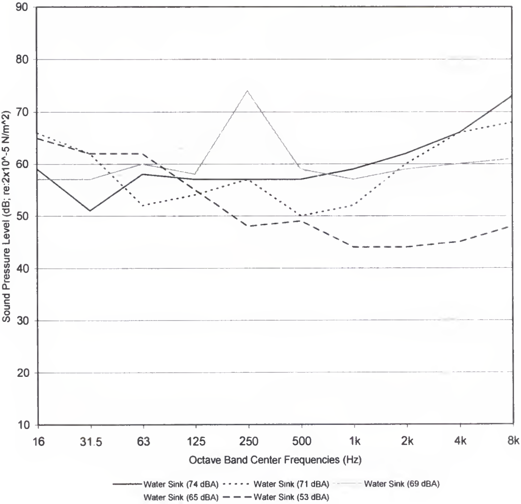


Figure B-5. Noise spectra and levels of water running noise from sinks measured at noise source locations

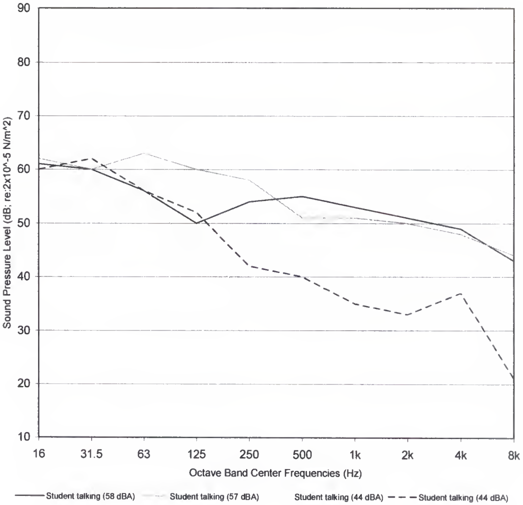


Figure B-6. Noise spectra of students' talks

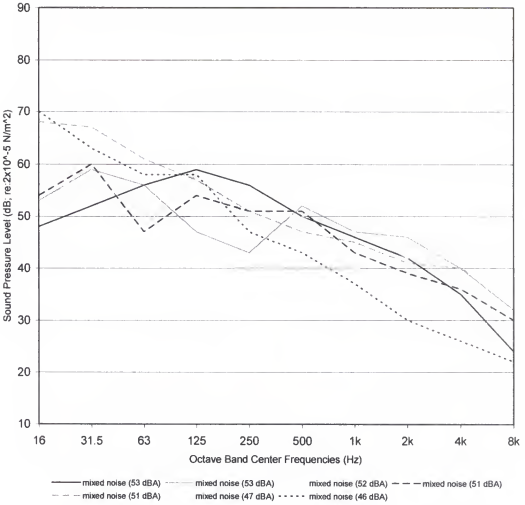


Figure B-7. Noise spectra and noise level of mixed noises at students seating areas

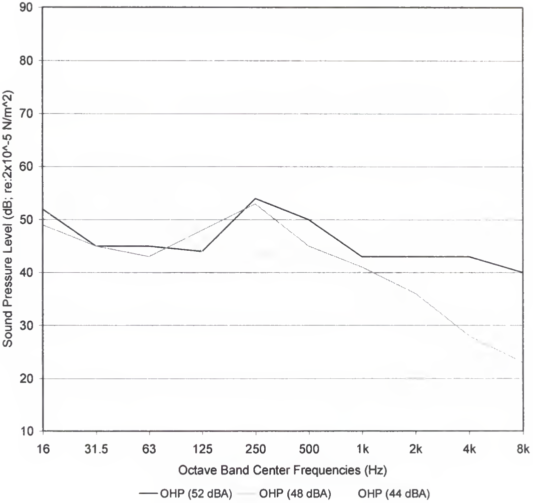


Figure B-8. Overhead projector noise spectra and noise levels measured at students' seating areas

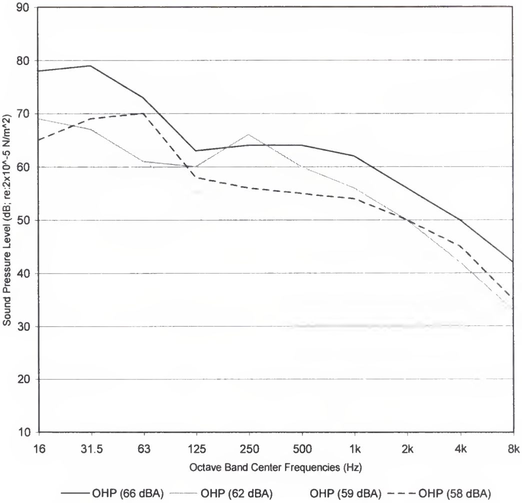


Figure B-9. Overhead projector noise spectra and noise levels measured at noise source locations

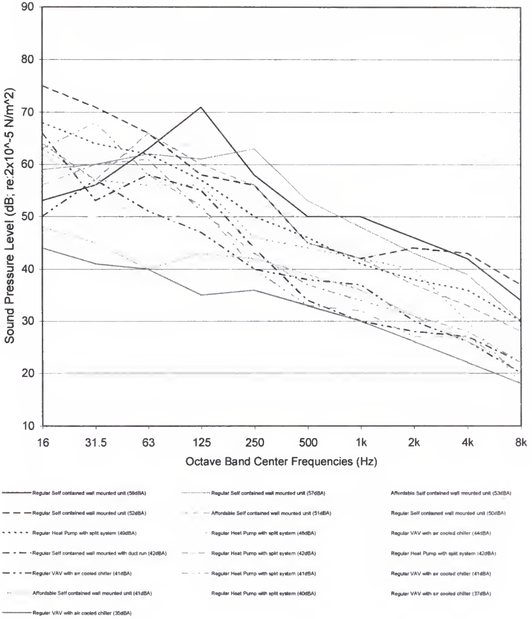


Figure B-10. Noise spectra and level from supply registers measured at students' seating areas

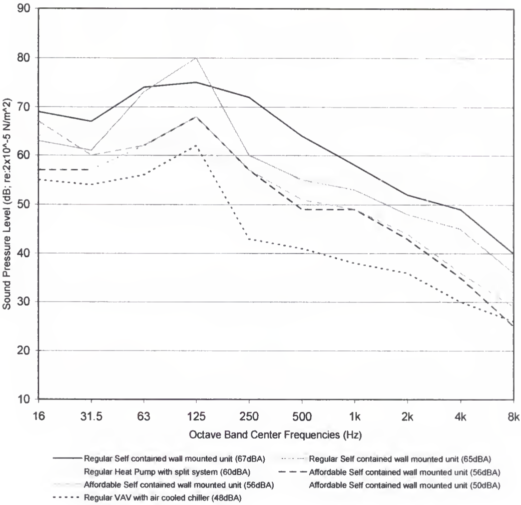


Figure B-11. Noise spectra and level from supply registers measured at noise source locations

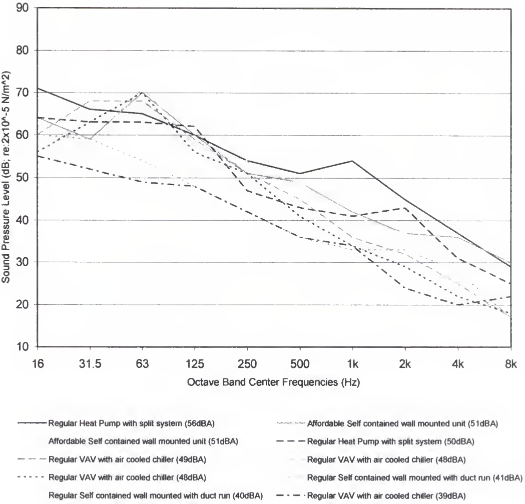


Figure B-12. Noise spectra and levels from return grills measured at students' seating areas

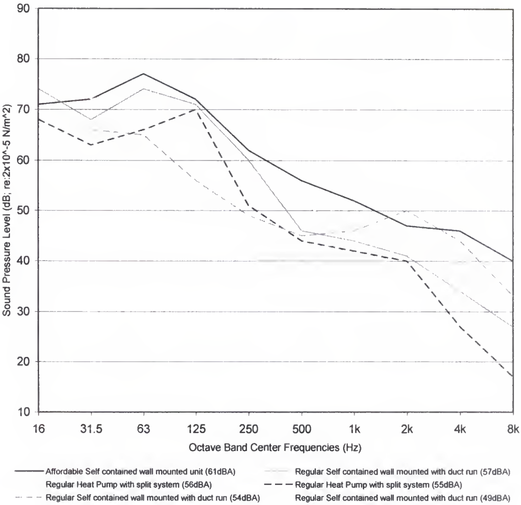


Figure B-13. Noise spectra and levels from return grills measured at source locations

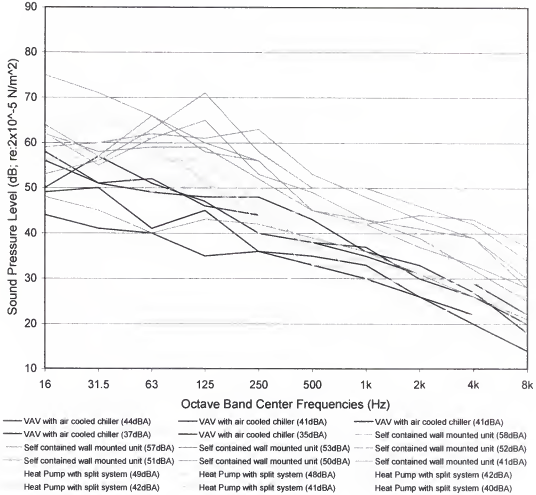


Figure B-14. Summary of noise from supply grills at students' seating areas

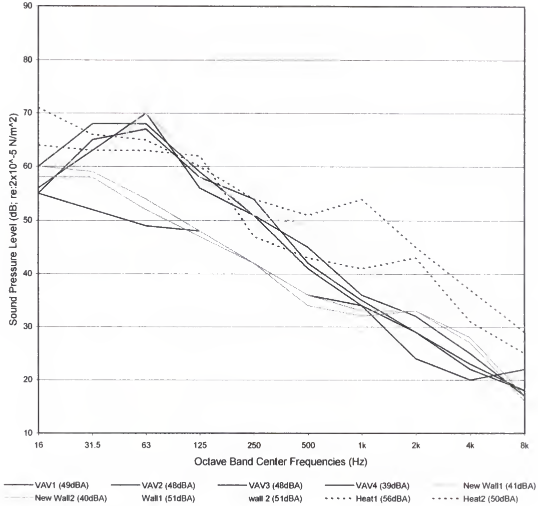


Figure B-15. Noise spectra of return grills measured at students' seating areas

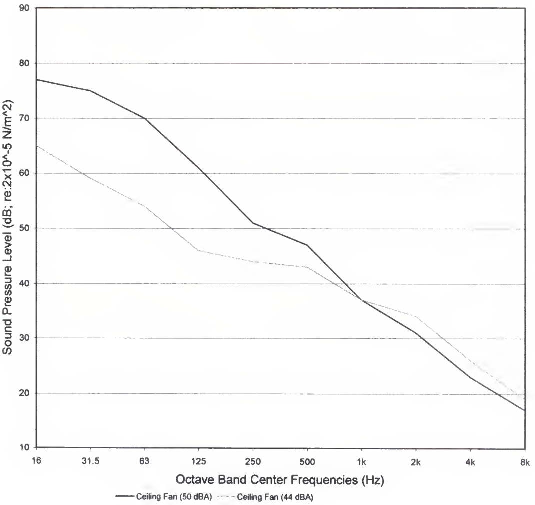


Figure B-16. Noise spectra of ceiling fan measured at students' seating areas

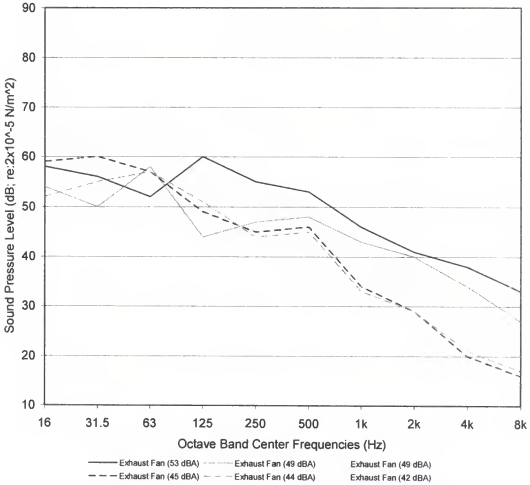


Figure B-17. Noise spectra of restroom exhaust fans measured at students' seating areas

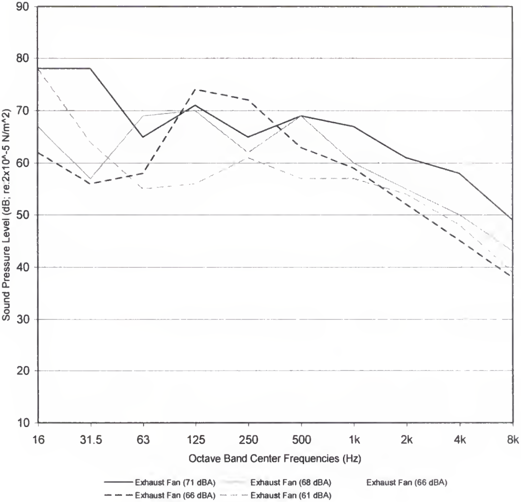


Figure B-18. Noise spectra of restroom exhaust fans measured at source locations

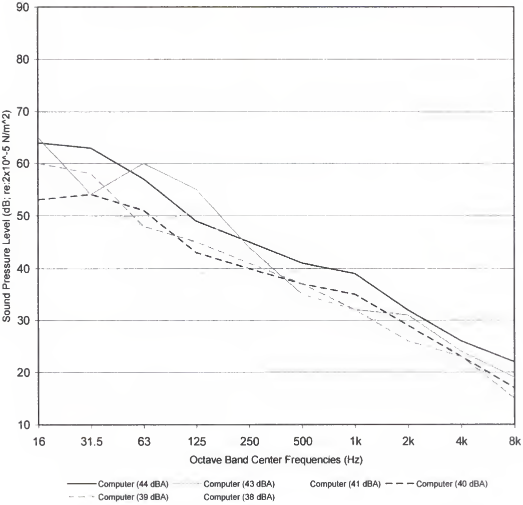


Figure B-19. Computer noise spectra measured at students' seating areas

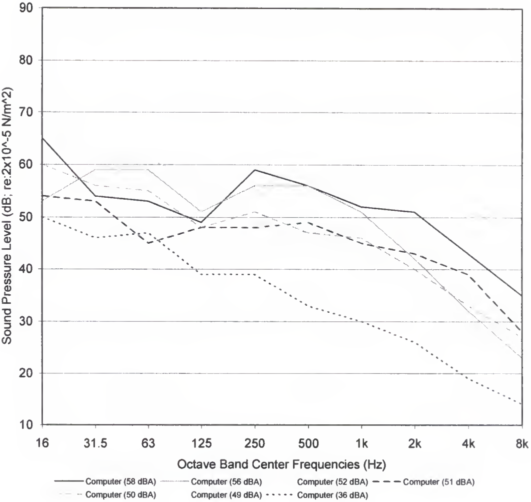


Figure B-20. Computer noise spectra measured at noise source locations

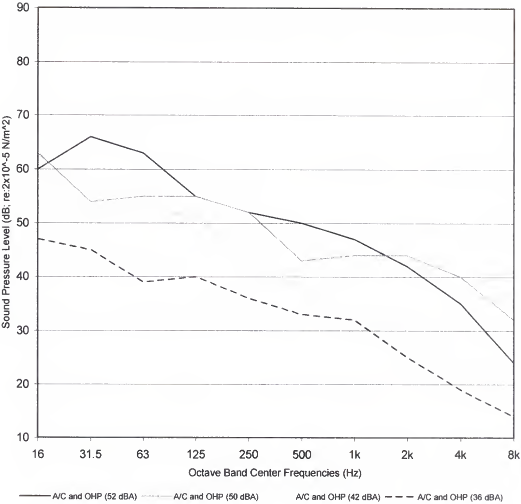


Figure B-21. Noise spectra of combined noise sources measured air-conditioning system and OHP noise at students' seating areas

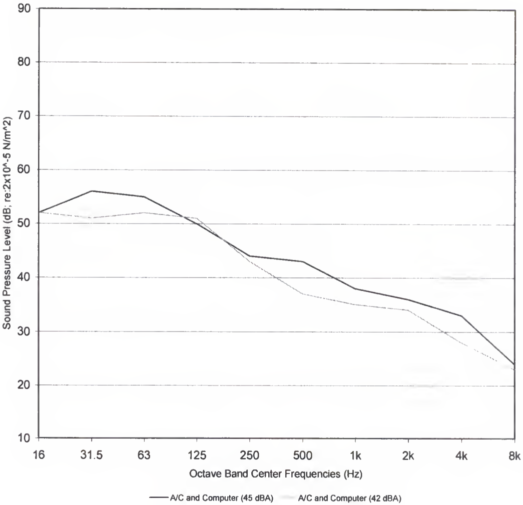


Figure B-22. Noise spectra of combined noise sources measured air-conditioning system and computer noise at students' seating areas

APPENDIX C
STATISTIC OF TEST SUBJECTS

Table C-1. Statistic of test 1 subjects

	Number	Average Age
Male Subjects	9	25.6
Female Subjects	4	25.5
Overall	13	25.5

Table C-2. Statistics of test 2 subjects

	Number	Average Age
Male Subjects	1	21
Female Subjects	18	21.4
Overall	19	21.4

APPENDIX D
NOISE SOURCE CORRELATION TEST

		Student Talks	A/C	Refrige-rator	O H P	Mixed Noises	Exheust Fan	Dehumidi-fier	Computer	Ceiling Fan	Ballast Noise	Ambient Noise	A/C Supply	A/C Return	A/C & Water Sink	A/C & O H P	A/C & Computer	Water Sink
Student Talks	Pearson Correlation	1 000	876	850	803	919	942	793	958	967	962	943	957	959	887	950	955	253
	Sig (2-tailed)		001	002	005	000	.000	006	000	.000	.000	000	000	000	.001	.000	000	480
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
A/C	Pearson Correlation	876	1 000	864	944	950	940	868	945	946	908	940	918	902	789	950	897	019
	Sig (2-tailed)	001		001	000	000	000	.001	000	000	000	.000	000	000	.007	000	000	959
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Rafrigerator	Pearson Correletion	850	864	1 000	929	952	931	953	924	915	861	944	949	938	892	943	943	165
	Sig (2-tailed)	002	001		000	000	000	000	.000	.000	001	000	000	000	.001	000	000	649
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
O H P	Pearson Correlation	803	944	929	1 000	941	936	951	904	905	867	923	909	902	810	.930	894	014
	Sig (2-tailed)	.005	000	.000		000	.000	000	000	000	001	000	000	000	005	000	000	969
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Mixed Noisa Source	Pearson Correlation	919	.950	.952	941	1 000	975	947	976	975	933	978	980	972	883	985	978	.041
	Sig (2-teiled)	000	000	.000	000		000	000	000	000	000	.000	000	000	001	000	000	910
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Exhuast Fan	Peerson Correletion	942	940	931	936	975	1 000	913	984	990	967	989	988	988	.921	989	975	.145
	Sig (2-tailed)	.000	000	.000	000	000		000	000	000	.000	000	000	000	000	000	000	689
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Dehumidifier	Pearson Correlation	793	868	953	951	947	913	1.000	878	876	864	903	914	920	847	919	930	- 099
	Sig (2-tailed)	.006	.001	.000	.000	.000	000		.001	001	001	000	000	.000	002	000	000	785
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Computer	Pearson Correlation	958	945	924	904	976	984	878	1 000	996	951	997	990	976	902	990	968	197
	Sig (2-tailed)	000	000	.000	000	.000	.000	001		000	000	.000	000	000	000	000	000	585
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Ceiling Fan	Pearson Correlation	967	946	915	905	.975	990	876	996	1 000	966	992	988	982	901	988	973	179
	Sig (2-tailed)	.000	000	.000	.000	.000	000	001	.000		.000	000	000	000	.000	000	000	.621
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Ballast Noise	Pearson Correlation	962	908	861	867	.933	967	864	.951	966	1 000	.949	958	.975	895	963	967	067
	Sig (2-tailad)	000	000	001	001	.000	000	.001	000	.000		000	.000	000	000	.000	000	854
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Ambient Noise	Pearson Correlation	943	940	944	923	978	989	903	997	992	949	1 000	993	981	915	992	.971	189
	Sig (2-tailed)	000	000	000	.000	000	.000	000	000	.000	.000		000	000	000	.000	000	600
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
A/C Supply	Pearson Corraletion	957	918	949	909	980	988	914	990	988	958	993	1 000	993	942	.994	989	182
	Sig (2-tailed)	000	000	000	.000	000	.000	000	000	000	000	.000		000	000	000	000	614
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
A/C Return	Pearson Correlation	959	902	938	.902	.972	988	920	976	982	975	981	993	1 000	935	985	995	134
	Sig (2-tailed)	000	000	.000	000	000	000	000	000	.000	000	000	000		000	.000	.000	711
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
A/C and Water Sink	Pearson Correlation	887	789	892	810	883	921	847	.902	901	895	.915	942	.935	1 000	.930	929	269
	Sig (2-tailed)	001	007	001	005	001	000	002	000	.000	.000	000	000	000		000	000	453
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
A/C and O H P	Pearson Correlation	950	950	943	930	985	989	919	990	988	963	992	994	985	930	1 000	982	142
	Sig (2-tailed)	000	000	000	000	000	000	000	000	000	000	000	000	000	000		000	696
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
A/C and Computer	Pearson Corralation	955	897	943	894	.978	975	930	968	973	967	971	989	995	929	982	1 000	088
	Sig (2-teiled)	000	000	000	000	.000	000	000	000	000	000	000	000	000	000	000		809
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Water Sink	Pearson Correletion	253	019	165	014	041	.145	- 099	197	179	067	189	.182	134	269	.142	088	1 000
	Sig (2-tailed)	480	959	649	969	910	689	785	585	621	854	600	814	711	453	696	809	
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10

APPENDIX E
CORRELATIONS BETWEEN MRT AND NOISE SOURCES

Table G-1. Correlations between MRT test material and noise sources at 65 dBA

		Running water noise at sink (W65)	Air-conditioning noise at return grill (A65)	Modified Rhyme Test material (MRT65)
W65	Pearson Correlation	1.000	0.140	-0.614
	Sig. (2-tailed)	.	0.700	0.059
	N	10	10	10
A65	Pearson Correlation	0.140	1.000	0.121
	Sig. (2-tailed)	0.700	.	0.740
	N	10	10	10
MRT65	Pearson Correlation	-0.614	0.121	1.000
	Sig. (2-tailed)	0.059	0.740	.
	N	10	10	10

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BIOGRAPHICAL SKETCH

Bumjun Kim was born in South Korea on October 24, 1970. He received his Bachelor of Engineer degree in civil engineering at Korea University (Seoul, South Korea) in 1995. After industry experience at Hyundai Development Company in Korea, he came to the United States and completed a master's degree in building construction at the University of Florida in 1998. During his Ph.D. program at the University of Florida, he specialized in architectural acoustics. He taught environmental technology classes with Professors Gary Siebein and Martin Gold during his program. He is now looking for an opportunity to serve his family and community.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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